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Targeted Gas Spectroscopy Using Tunable VCSELs

T. Bond, M. Bora, A. Chang, J. Mccarrick

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Targeted Gas Spectroscopy Using Tunable VCSELs

JOWOG 28 Main Meeting

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6/27-30/2011

Tiziana Bond, Mihail Bora, Allan Chang, Jim McCarrick

Lawrence Livermore National Laboratory, P. O. Box 808, Livermore, CA 94551

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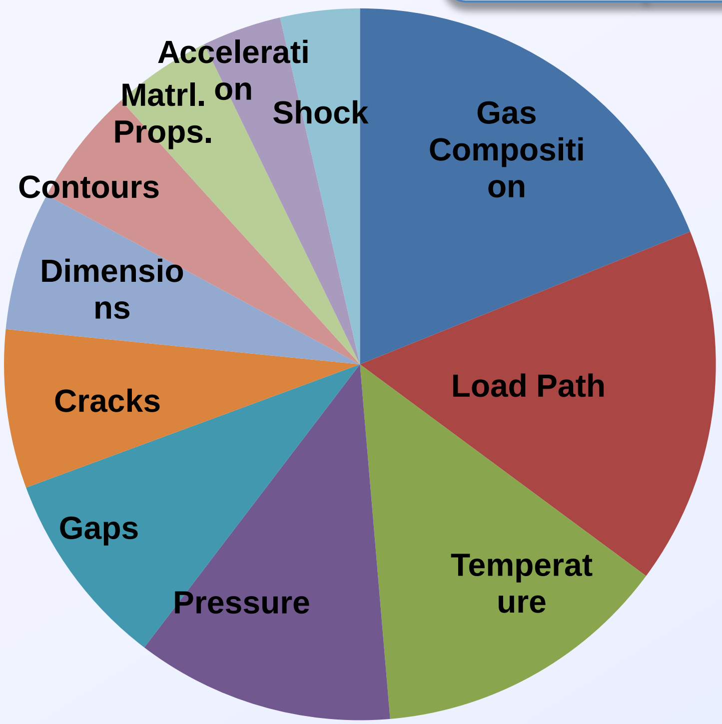
- **Motivation**
- **Background**
- **Measurements (Setup and results)**
  - Basic Absorbance
  - Wavelength Modulation
- **Conclusion**
  - Steps forward

Persistent Surveillance of complex systems by embedded sensing: a new paradigm of aging awareness and monitoring

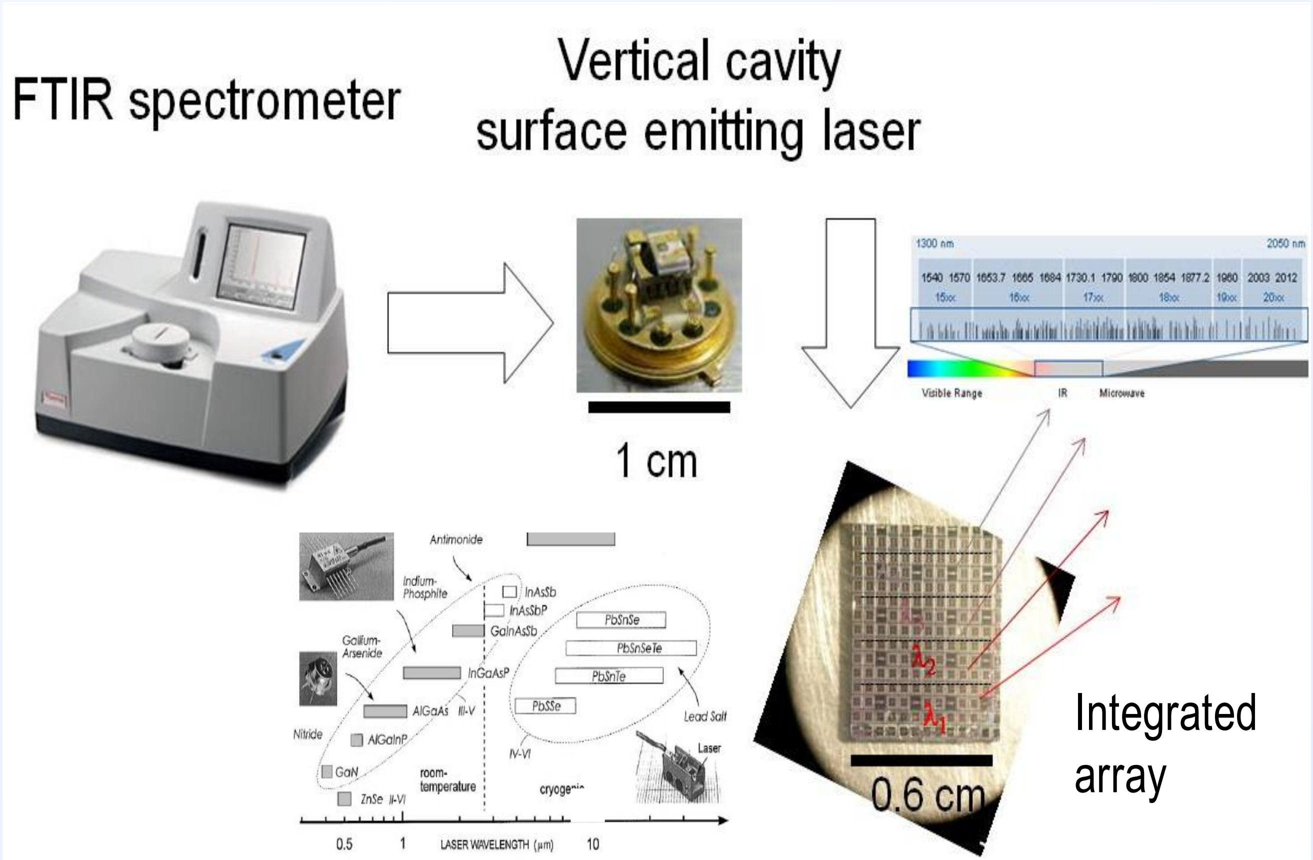
Gas sensing will provide early detection of a broad range problems (decomposing components, corrosion, failures, etc)



Gas Sensing System Requirements

- Detection of mixtures of unknown species
- High sensitivity - ppm level of detection
- High selectivity – broad range of gas molecules (e.g. diatomics, organics, inorganics)
- Fiber optic compatible
- Rugged, robust system (lifespan = decades)
- **Minimize SWaP (size, weight, and power)**

Develop a chip scale sensor spectrometer for minimally invasive monitoring of targeted trace gases

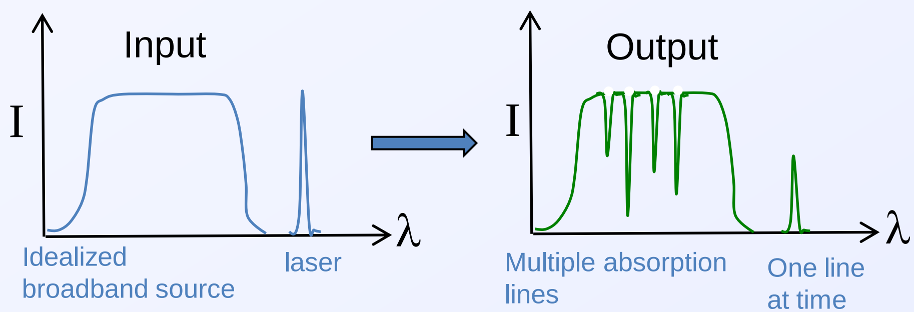


Approach: Exploit maturity and developments in tunable **VCSEL** technology for *broadband **TDLAS** (Tunable Diode Laser Absorption Spectroscopy*

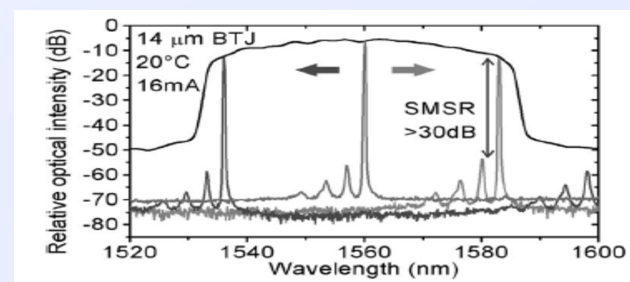
Application: atmospheric chemistry, combustion research, space exploration, industrial processing and emission monitoring, and toxic gas detection

VCSEL-based Gas Sensing of Targeted Gases: General Concept

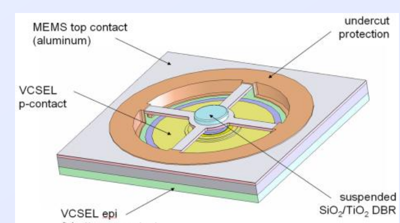
- **Absorption Spectroscopy:** measuring the concentration of gases by the strength of their infrared (IR) absorption fingerprint:



Molecules	λ (nm)
H_2O	1390,1802,1854,1870,2360
CO_2	789,1960,2003,2012
CO	1570, 2360
NO	1800, 2650
NO_2	680
N_2O	1380,1960,2260
CH_4	1650, 1684,2360
NH_3	1500
C_2H_2	1520
O_2	760

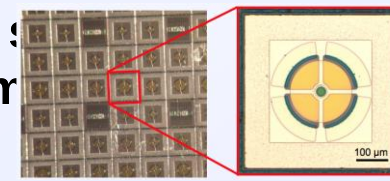


- **Vertical Cavity Surface-Emitting Lasers (VCSELs): compact, low-power**
  - Amplified wavelength is selected by cavity properties from a ~50 nm natural range
  - Cavity can be tuned thermally (~5 nm max) or via MEMS (10s of nm)
  - Bandgap engineering: commerical devices now exist w/ center wavelengths into the mid-IR (2.3 μ) at room temperature



Specific Approach: closed-cavity, open-path VCSELs gas sensing tests

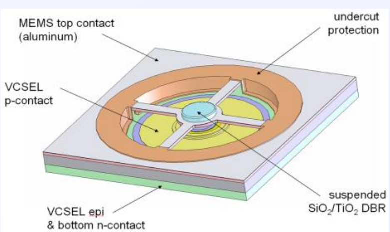
- **Ultimate goal: a battery of tunable devices which cover a s number of targeted gases of interest, combined onto a sm**

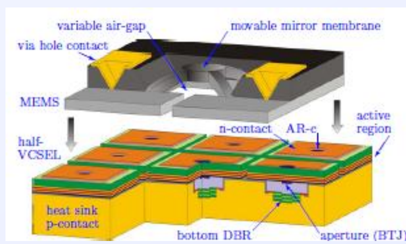


TDLAS (tunable diode laser absorption spectroscopy)

Collaboration to fabricate open-cavity, MEMS-tunable (R&D) @ 760, 1550, 2300nm

Use of commercial closed-cavity, current-tuned devices w/ external sensing path
COTS@ 760, 1392,1550, 1854, 2012nm





Minimize external path, e.g. via wavelength modulation

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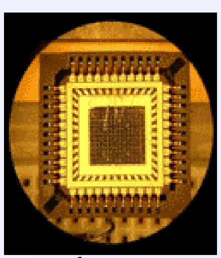
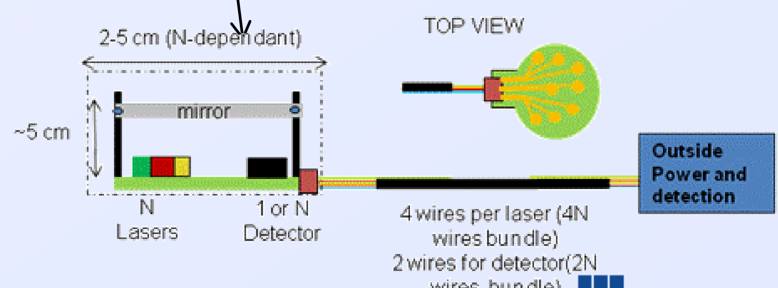
Darmstadt Univ./Schottky Institute

Height~1-2cm
100s devices

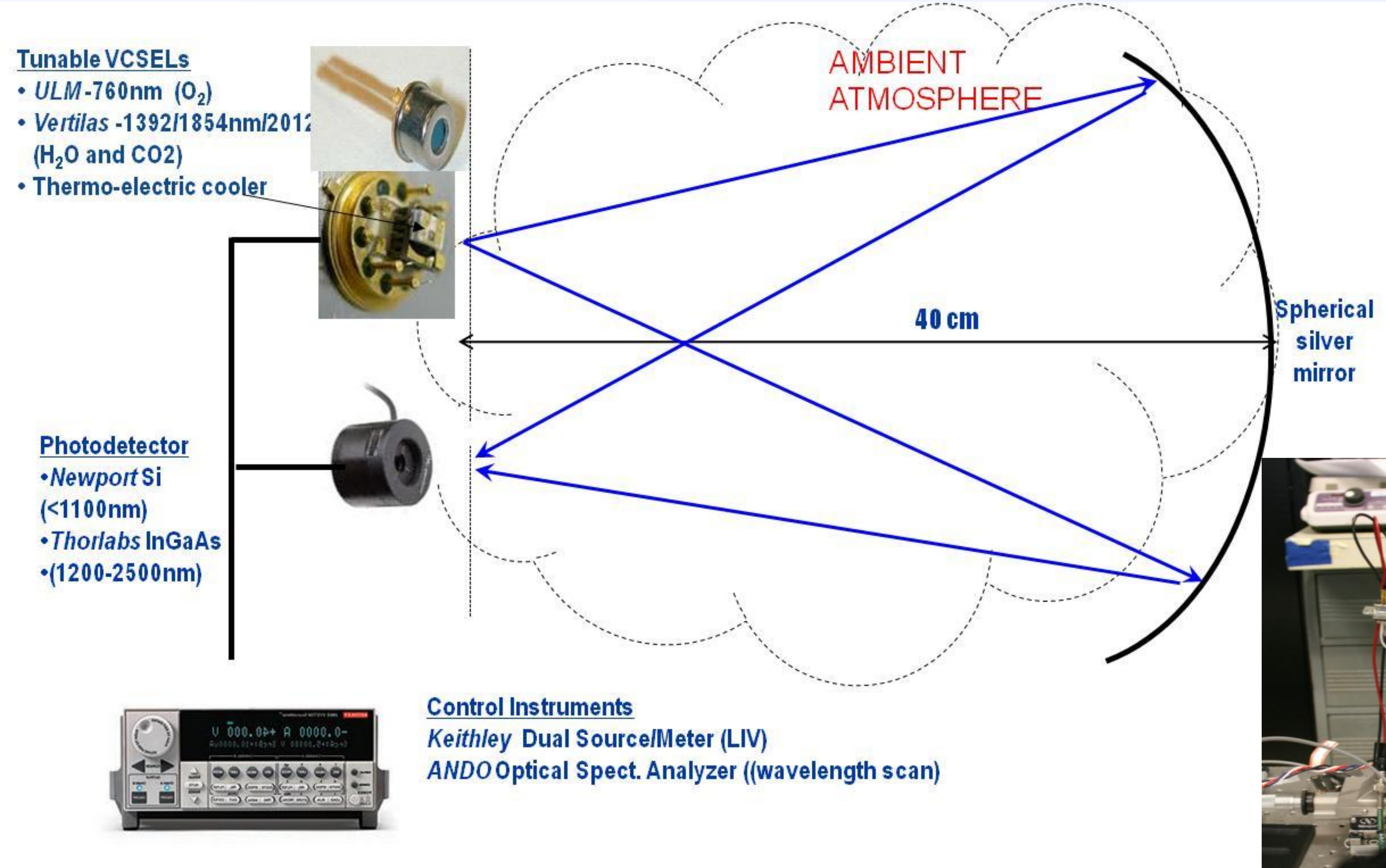


1-2 cm

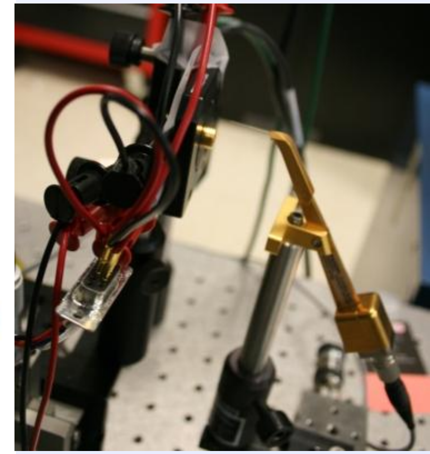
Integration, Packaging and Multiplexing

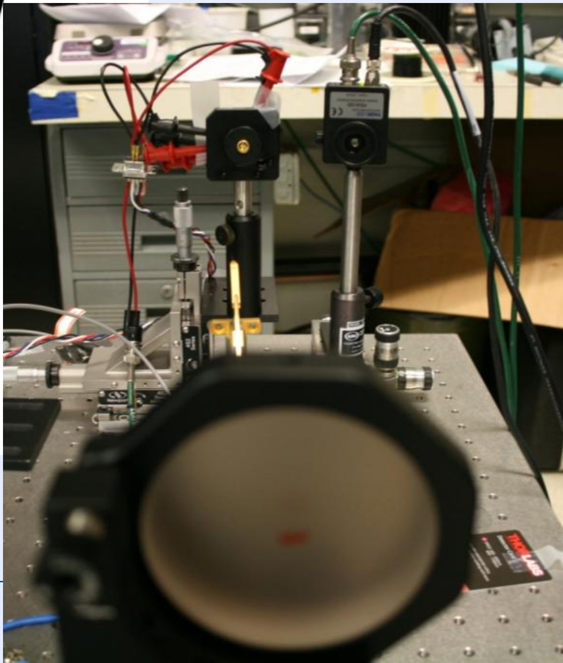


Closed-cavity, open-path VCSELs gas sensing tests

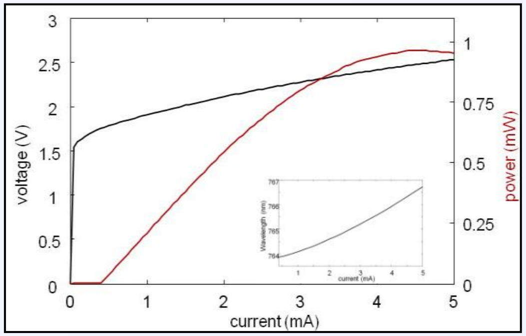


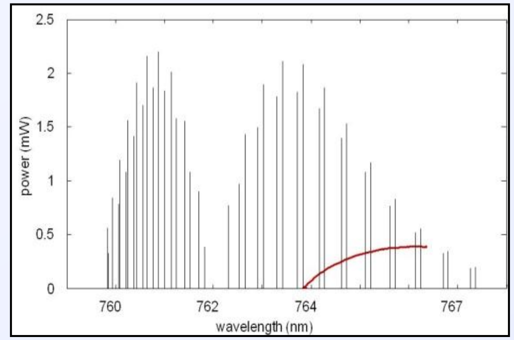
Cascade Fiber Probe

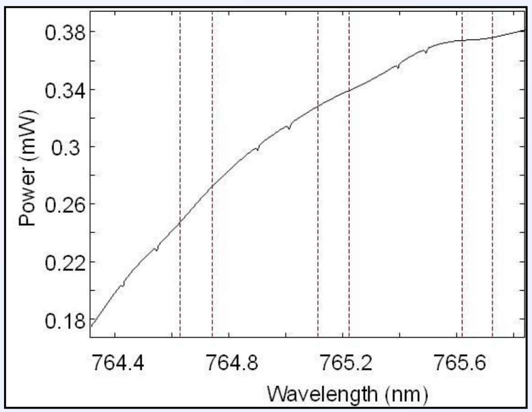


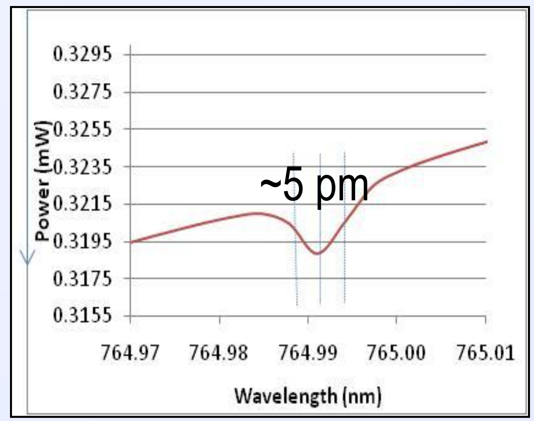


O_2 detected in ambient air (21%) with 763nm VCSEL









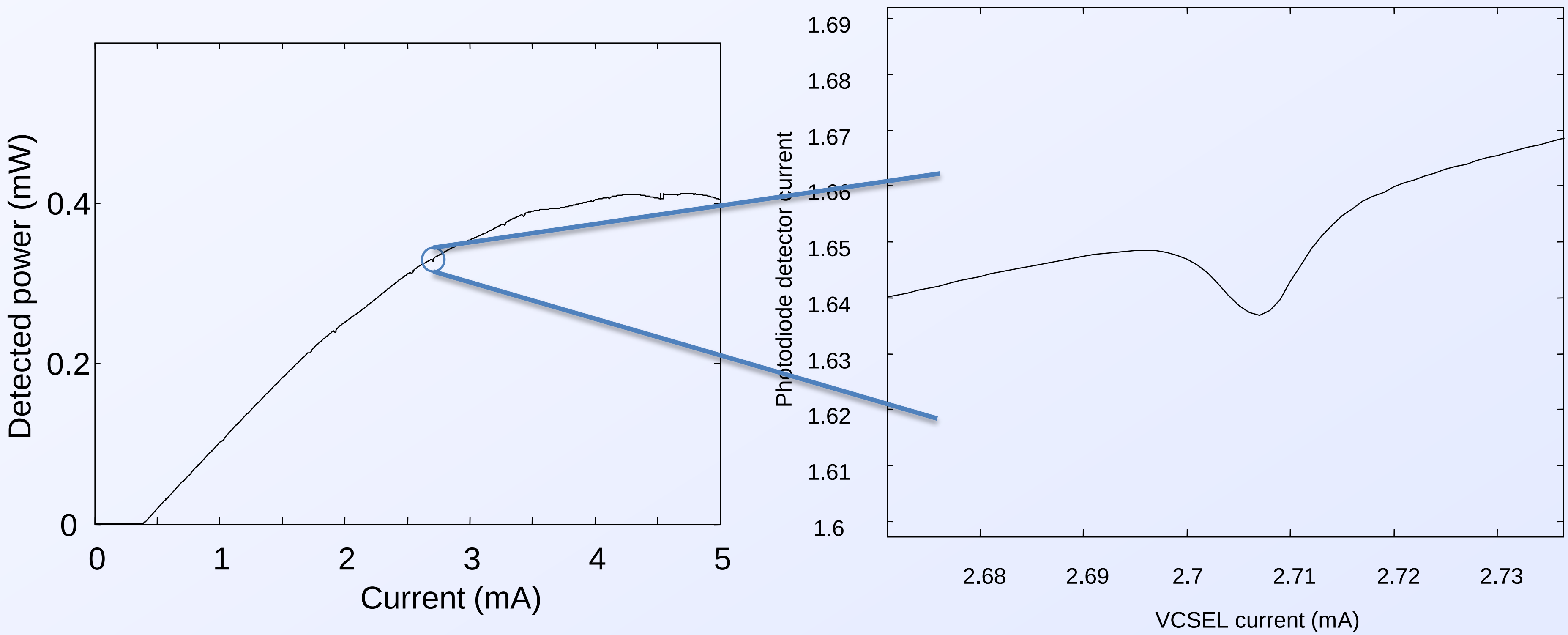
<u>Quench is clearly observable</u>

- Signal change due to oxygen absorbance: $\Delta P/P \sim 1\%$
- Absorption line is above the noise level (<0.5uW)
- Measurement of O_2 concentrations > 0.5% are possible
- Scaling to open-cavity possible (~1um gap and $Q \sim 10^5$)

$$A = T/T_0 = \exp(-\alpha L_{eff}) = \exp(-\sigma_g C_g Q L)$$

Preliminary experiments have shown wavelength modulation can greatly improve signal-to-noise

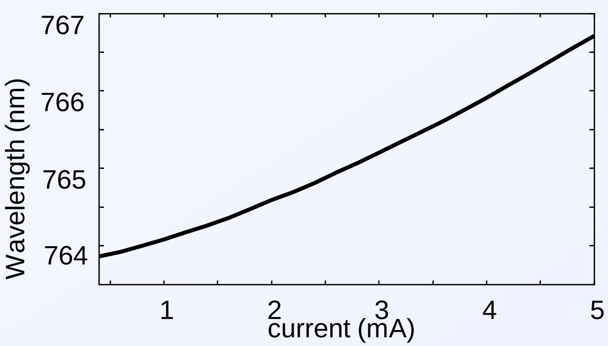
- **At low concentrations or with weakly absorbing gases, absorption fingerprint is just a slight bump on the background intensity**



Ambient O_2 detection w/ 763 nm COTS VCSEL

Wavelength modulation pulls the bump out of the background by making it a time-varying signal

- **Modulating the laser drive current modulates the output wavelength**



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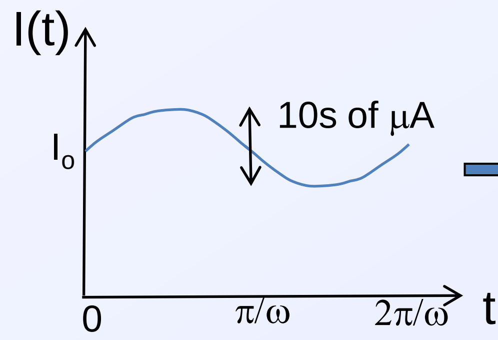
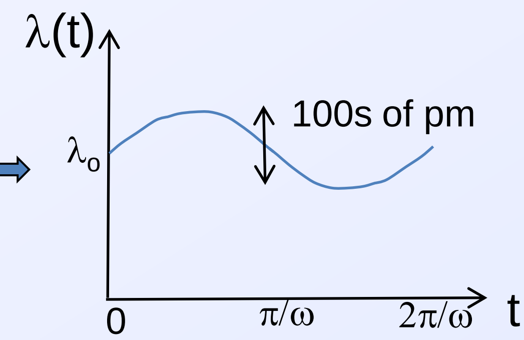
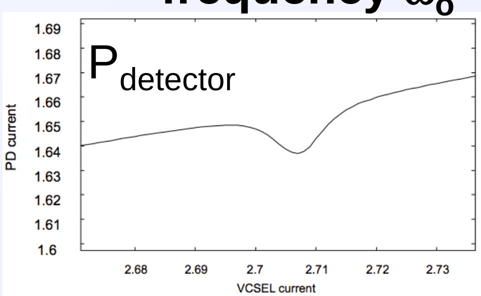




- **The detected signal is now periodic in harmonics of the modulation frequency ω_o**



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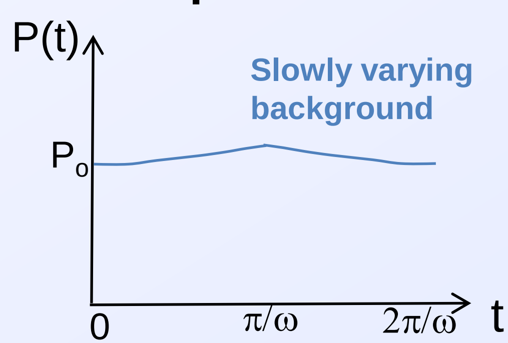

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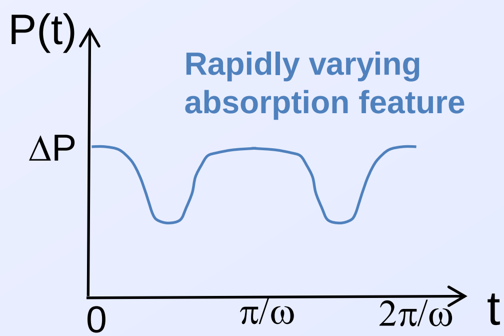
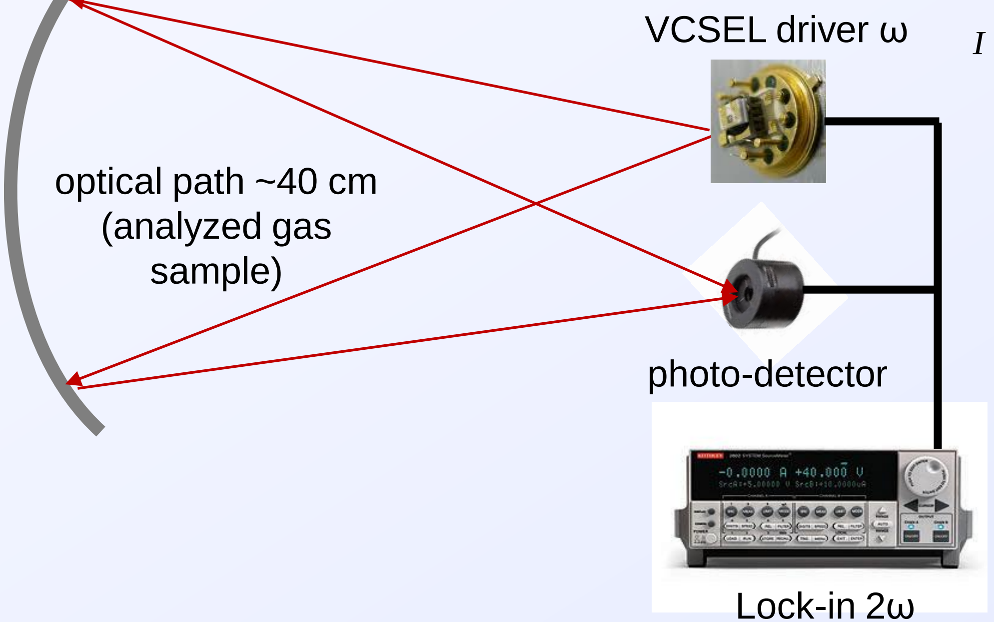
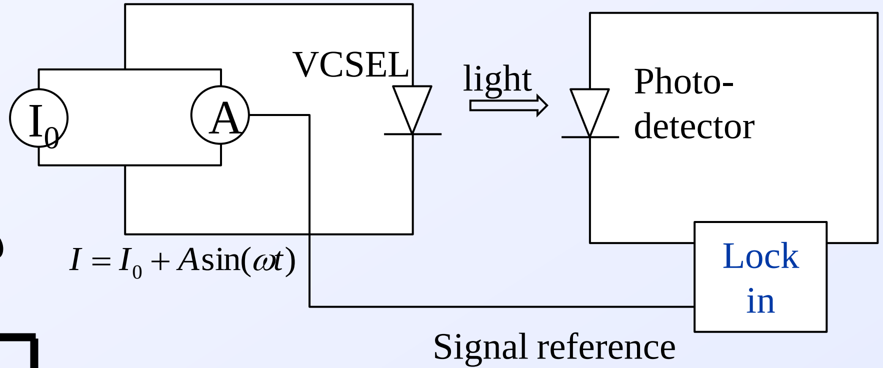


- **A lock-in amplifier then measures individual harmonic components with high signal-to-noise**

$$P_{lock-in}(n\omega_o, \phi) = \frac{1}{\Delta T}\int_t^{t+\Delta T} P_{detector}(t)\sin(n\omega_o t + \phi)dt$$

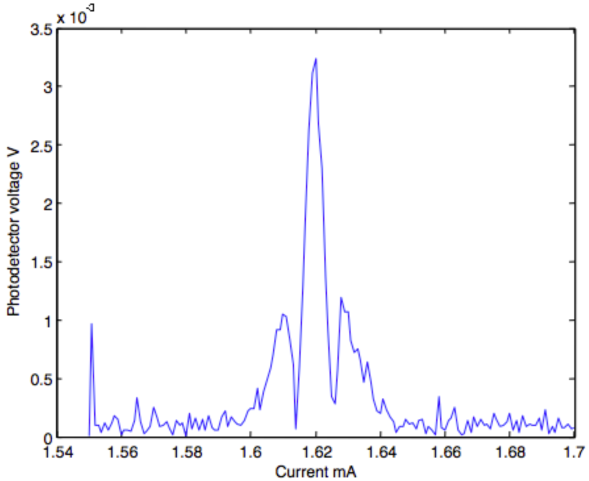
Modified measurement setup for wavelength modulation spectroscopy (WMS)



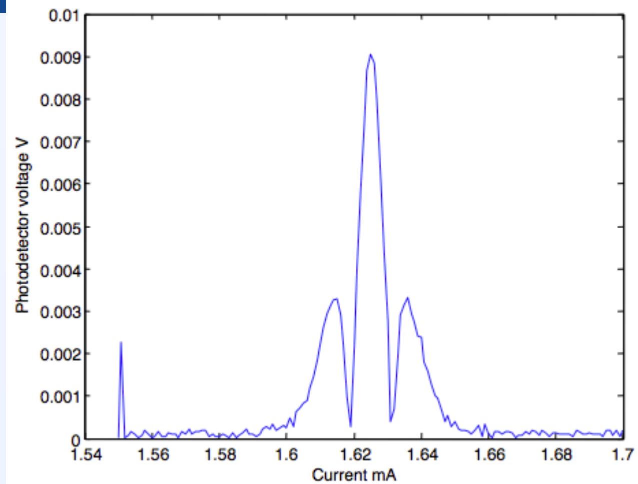


- **A series of lock-in measurements have been made at the 2ω component of the photo-detector signal**

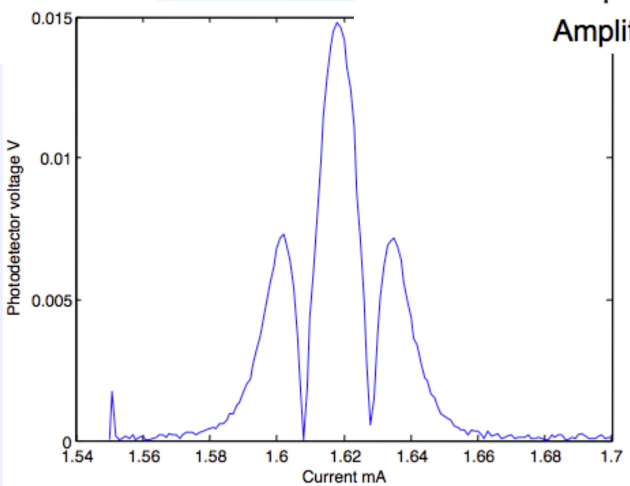
Parameter study in amplitude of current modulation; curves are versus I_o



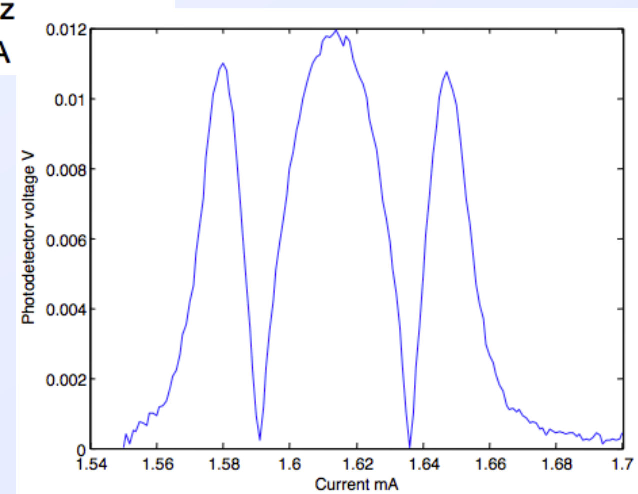
Frequency ω=10 kHz
Amplitude A = 5 μA



Frequency ω=10 kHz
Amplitude A = 10 μA

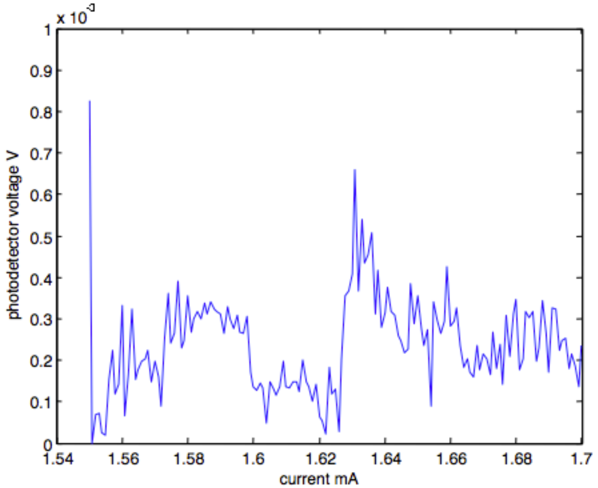


Frequency ω=10 kHz
Amplitude A = 20 μA

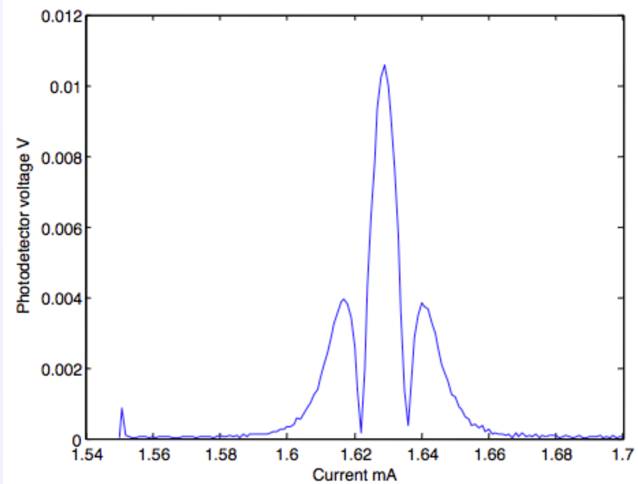


Frequency ω=10 kHz
Amplitude A = 50 μA

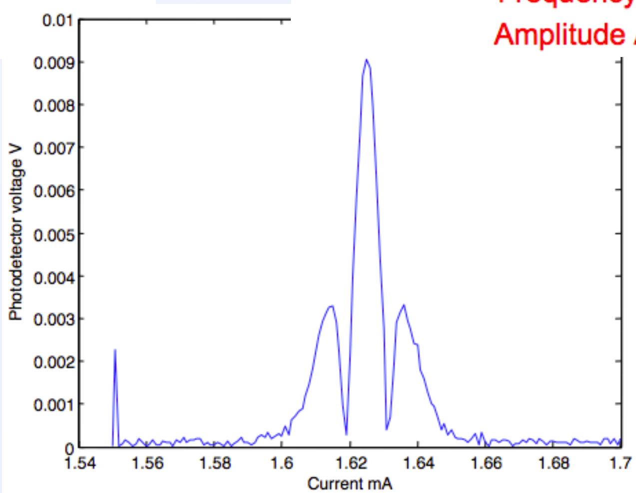
Parameter study in modulation frequency; curves are versus I_o



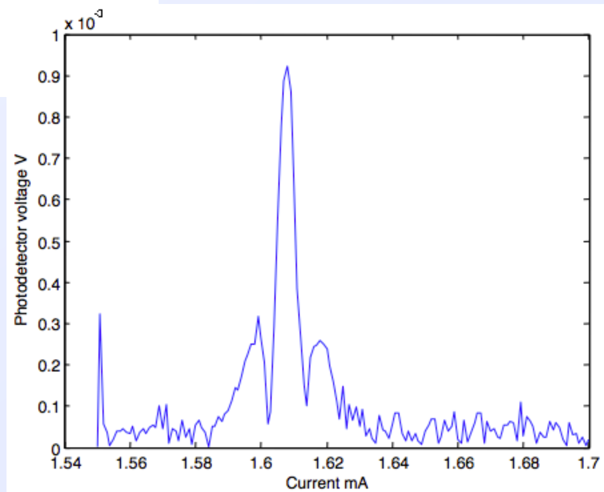
Frequency ω=10 Hz
Amplitude A = 10 μA



Frequency ω=1 kHz
Amplitude A = 10 μA



Frequency ω=10 kHz
Amplitude A = 10 μA



Frequency ω=40 kHz
Amplitude A = 10 μA

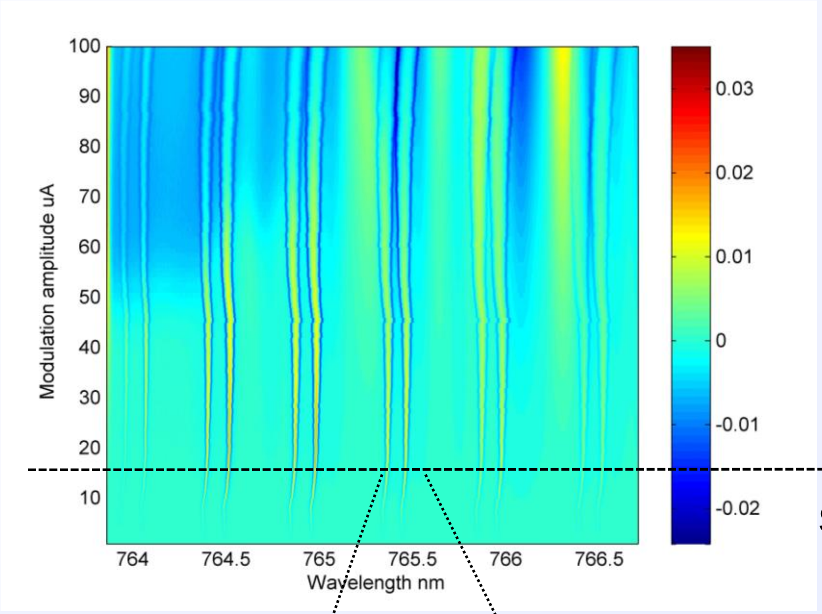
WMS amplitude scan: automated for full range analysis

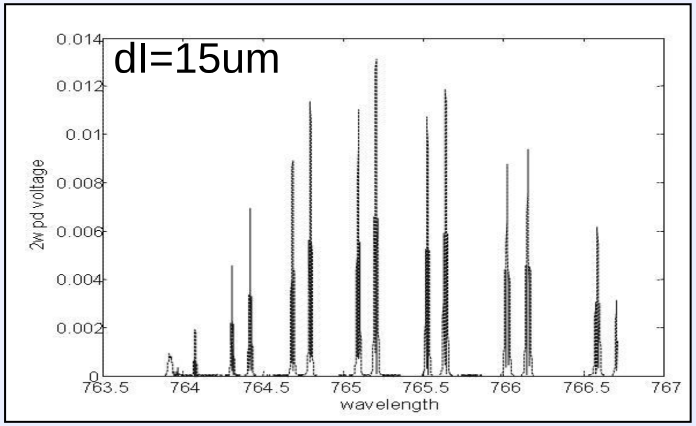
OXYGEN. Modulation freq 1 kHz; No T control

day

night

day





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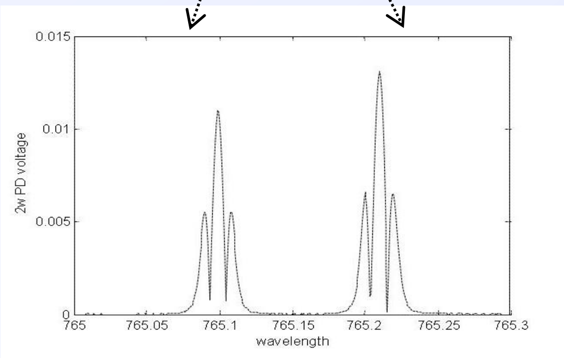
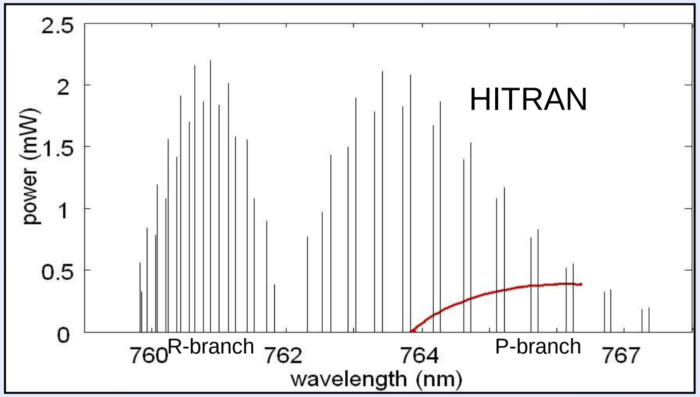
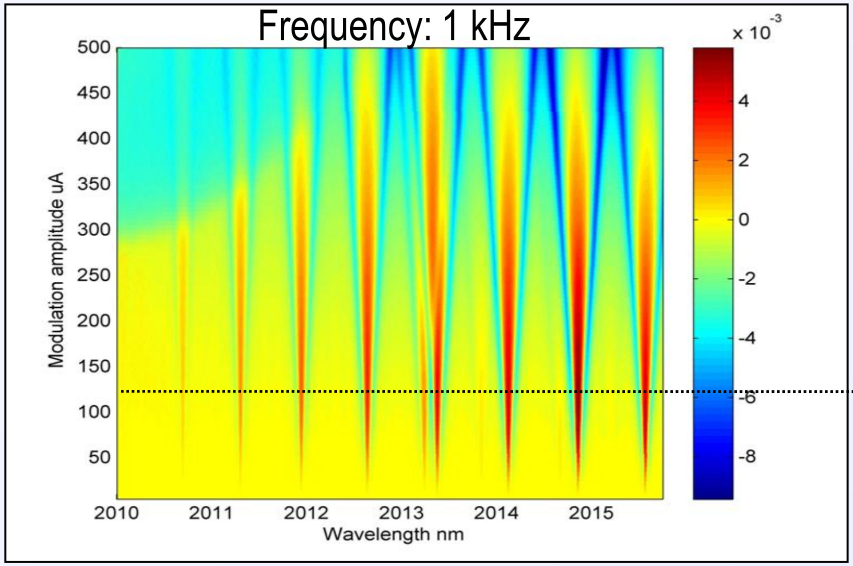
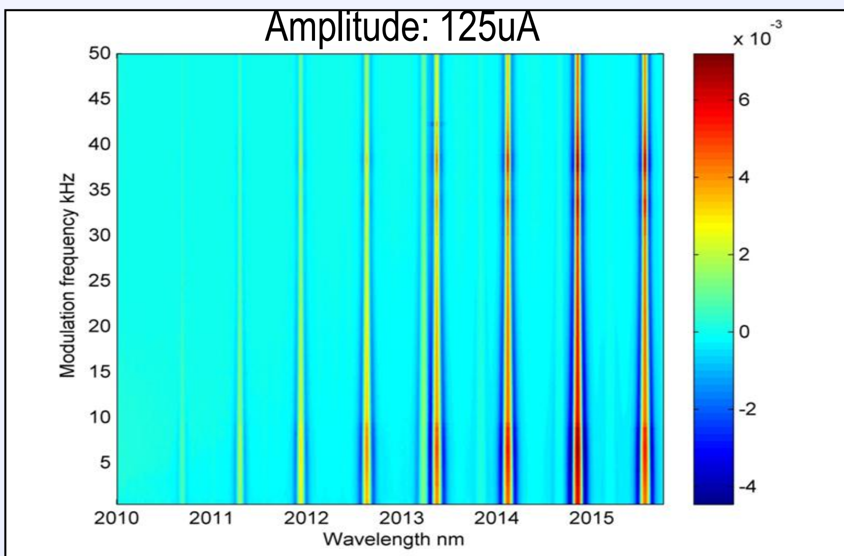




WMS of CO_2 in air (~400ppm): amplitude and frequency sweep





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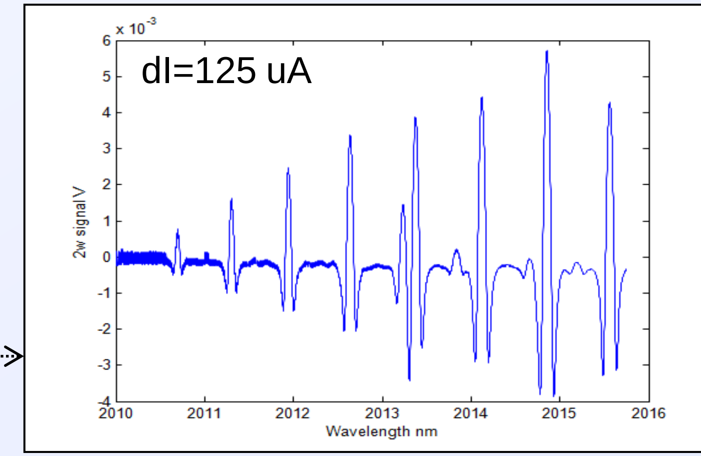
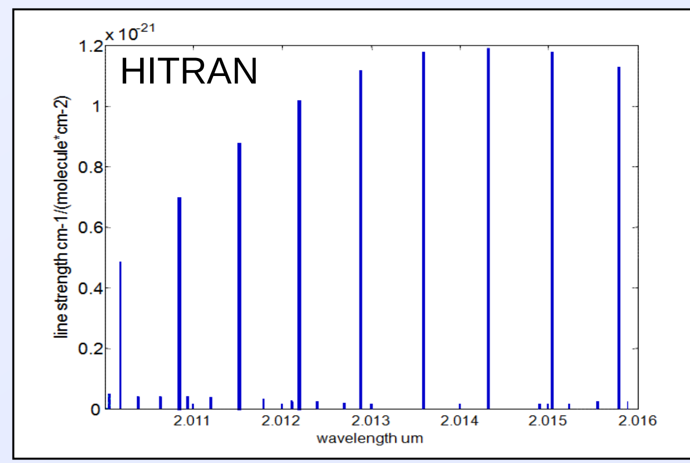
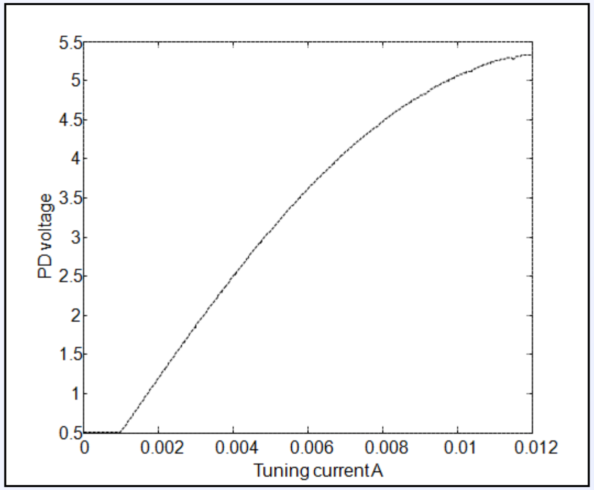
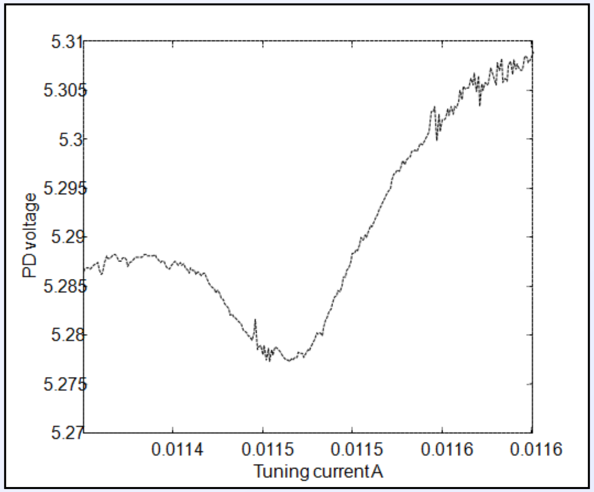




Signal to noise indicates drastic improvement of WMS over absorbance measurements

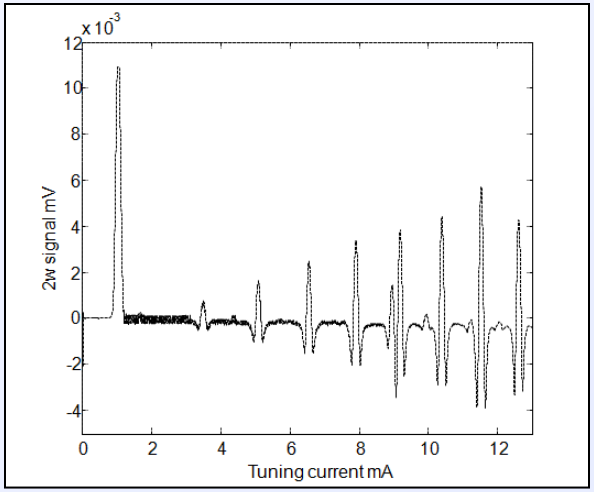
Absorbance

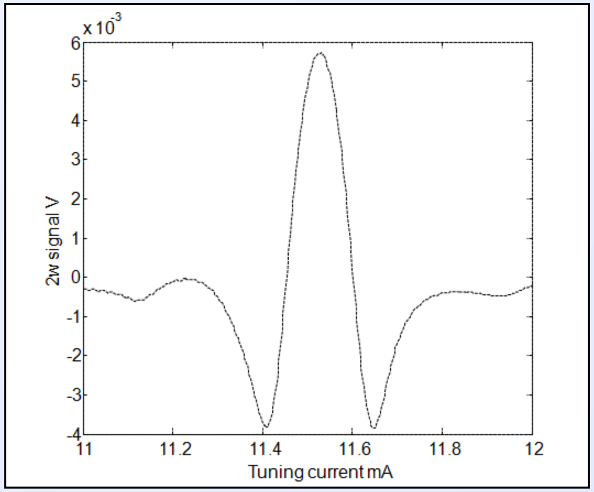




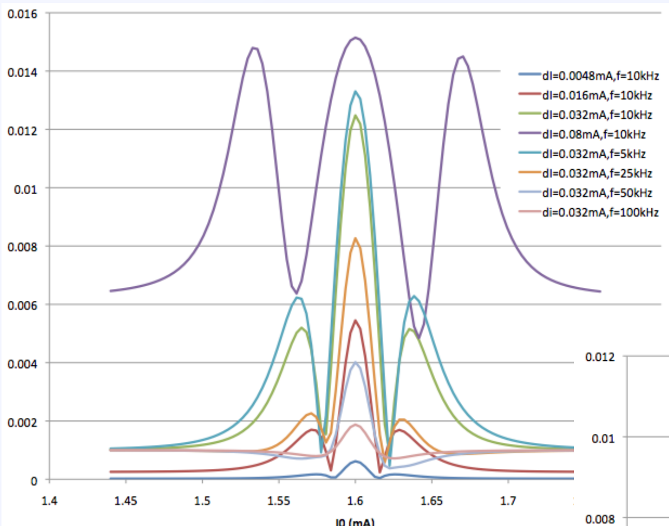
Wavelength Modulation

Tuning current:
0:0.002:13 mA
Amplitude: 125 uA
Frequency: 1 kHz



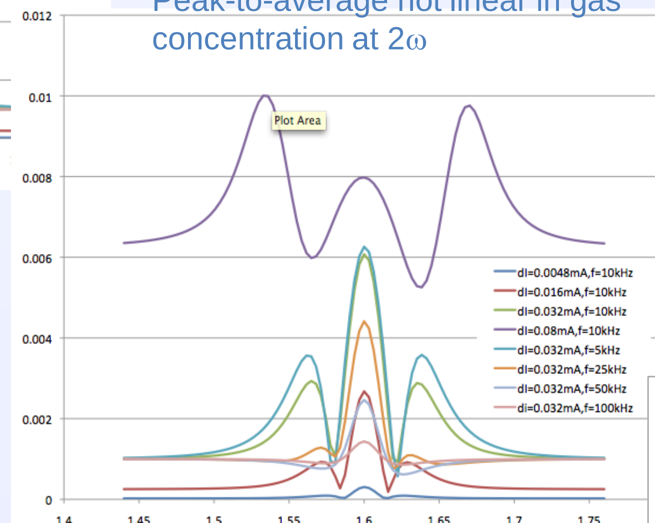


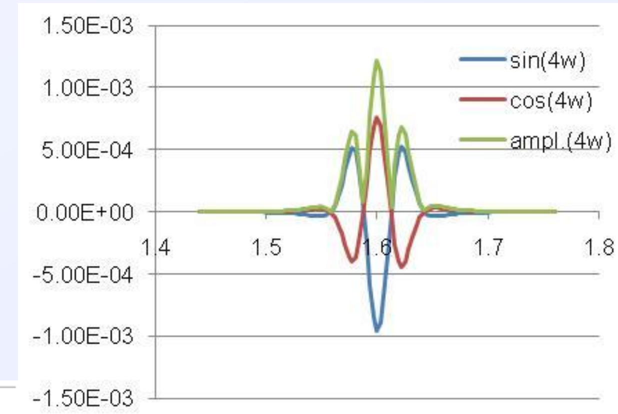
A model has been developed that may aid optimization



Features of experimental parameter studies captured in model

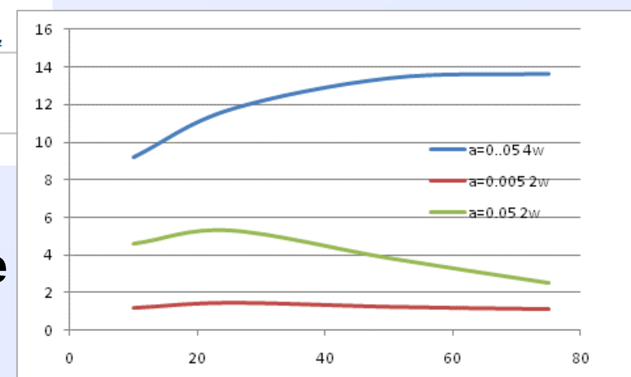
Peak-to-average not linear in gas concentration at 2ω





Possibly better peak-to-average signal at 4ω

Estimate how low absorption loss can be (concentration or path)



- **Preliminary model results do show the observed experimental features, and should offer guidance on defining what "optimal" is**

Conclusions

- **We propose tunable VCSELs in NIR TDLAS for monitoring and finger printing trace-gases in complex systems**

- **Wavelength modulation shows much improvement on direct absorbance and higher SNR**
  - **It removes 1/f noise for lower frequencies**
  - **The signal is tracked in a very narrow frequency band**
  - **It discriminates gas absorption from signal baseline degradation (e.g. fouling)**

- **An analytical model and fully-automated data collection/processing are used to guide and select the best conditions for highest SNRs**

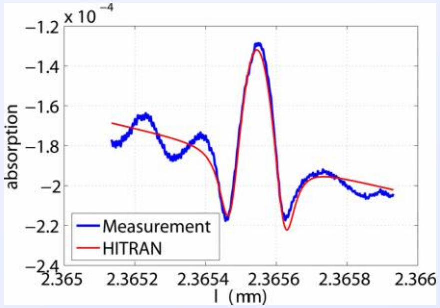
- **Lower detection limits can be achieved and need to be quantified to determine minimum path length and the path to miniaturization**
  - **Going form 80 cm to < 10cm path length seems feasible**

The path forward is comprised of parallel improvement of the devices and their usage

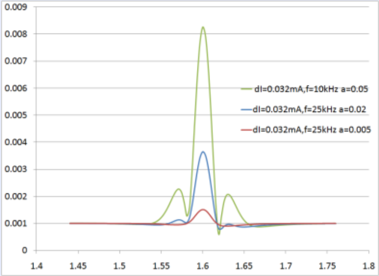
We pursue both practical fabrication of MEMS-tunable, open-cavity devices, and optimized use of existing closed-cavity devices

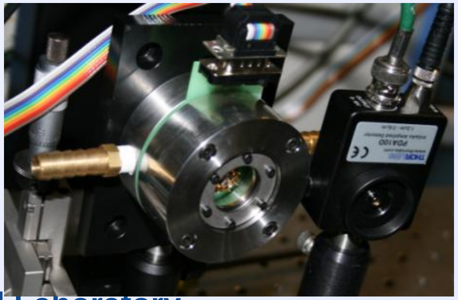
Specifics:

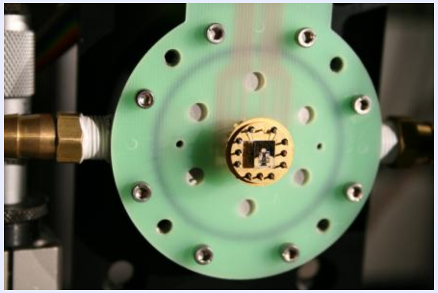
- Calibration of gas-mixer to perform measurements at other than ambient concentrations and for mixtures
- Quantify detection limits achievable with WMS of closed-cavity, external path VCSELs (scan and fit)
- Continue collaboration with German partners on device fabrication
  - Prototype MEMS-tunable 1560 nm devices supplied by the Technical Institute in Darmstadt



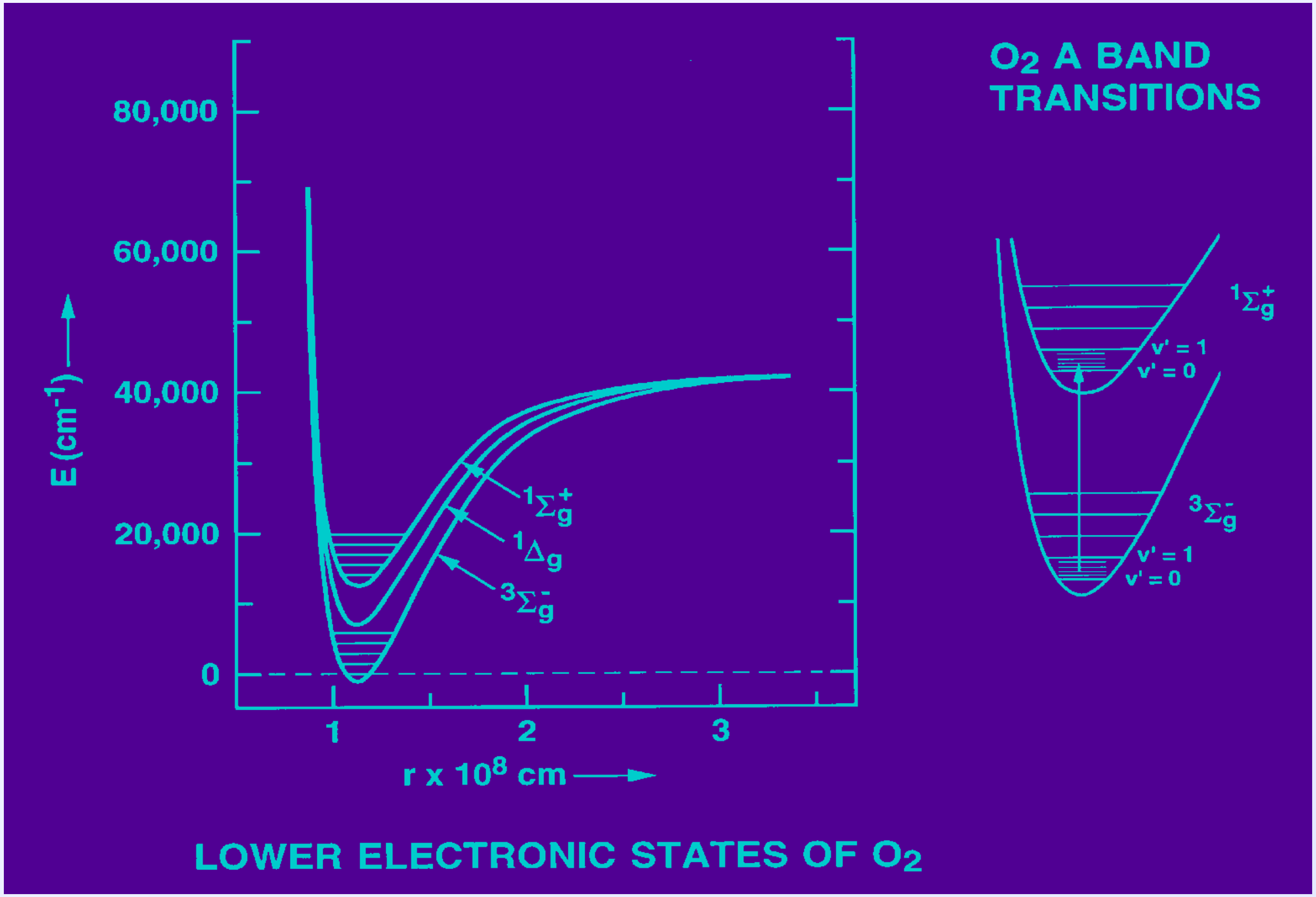
Hangauer, Opt. Lett 2008



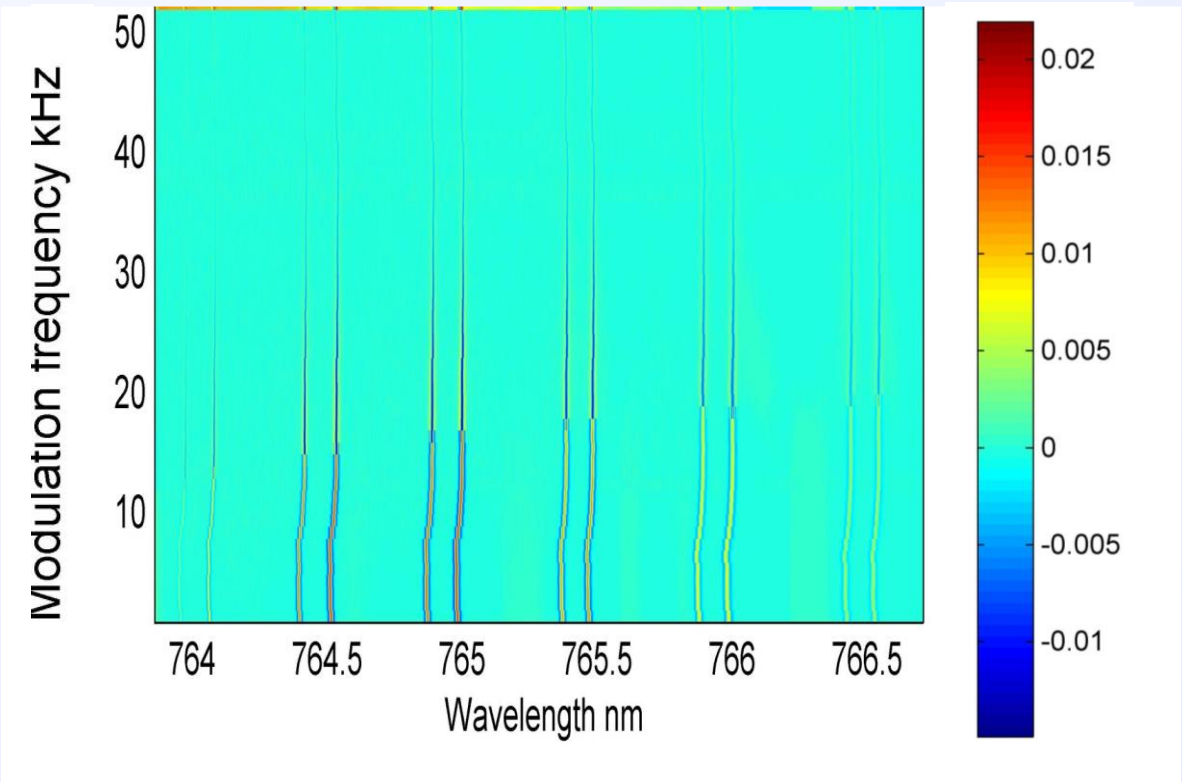


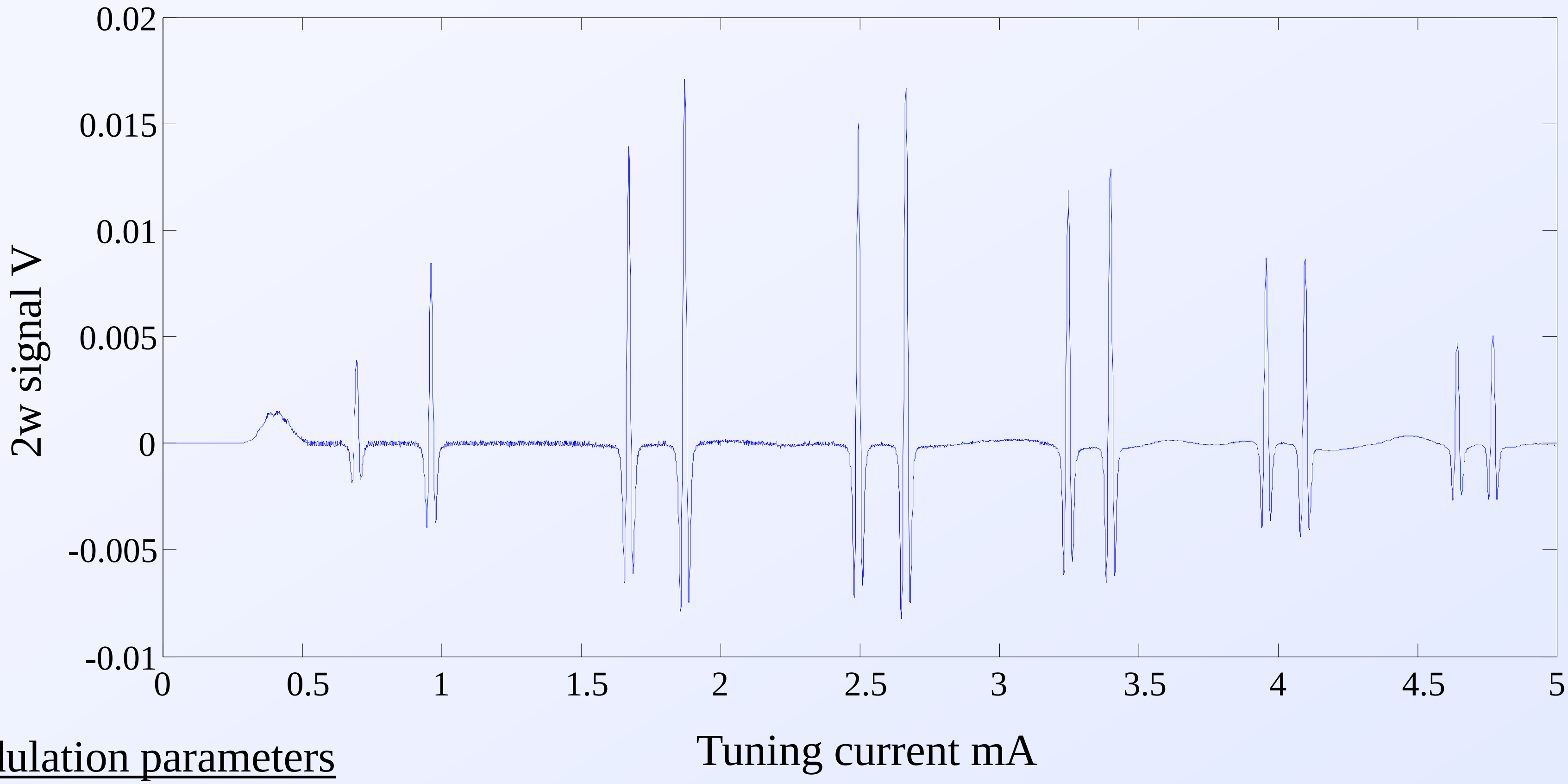


Questions?


80,000
60,000
40,000
20,000
0
E (cm^{-1})
1
2
3
r x 10^8 cm
$^1\Sigma_g^+$
$^1\Delta_g$
$^3\Sigma_g^-$
O$_2$ A BAND TRANSITIONS
$^1\Sigma_g^+$
v' = 1
v' = 0
$^3\Sigma_g^-$
v' = 1
v' = 0
LOWER ELECTRONIC STATES OF O$_2$

OXYGEN WMS: Frequency sweep

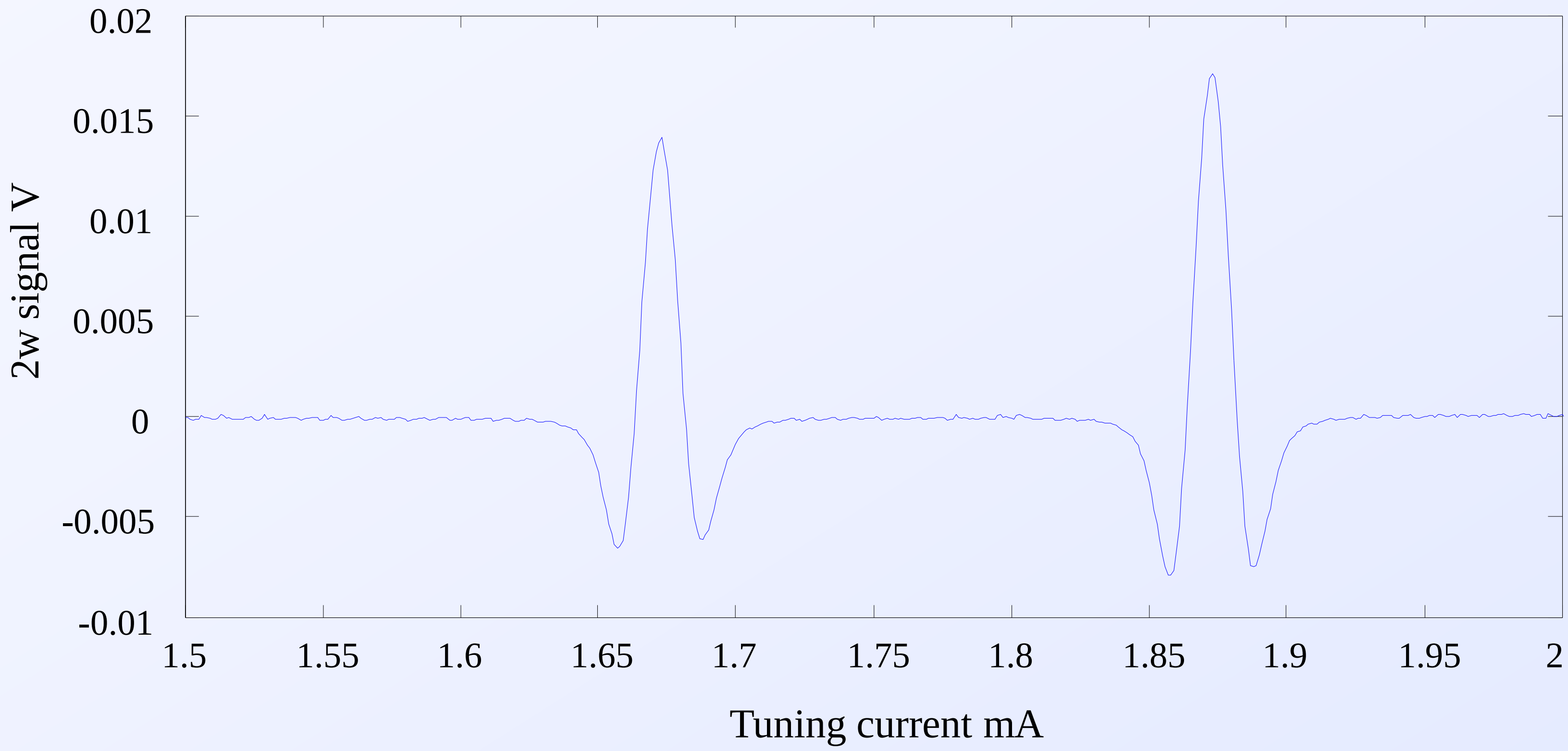




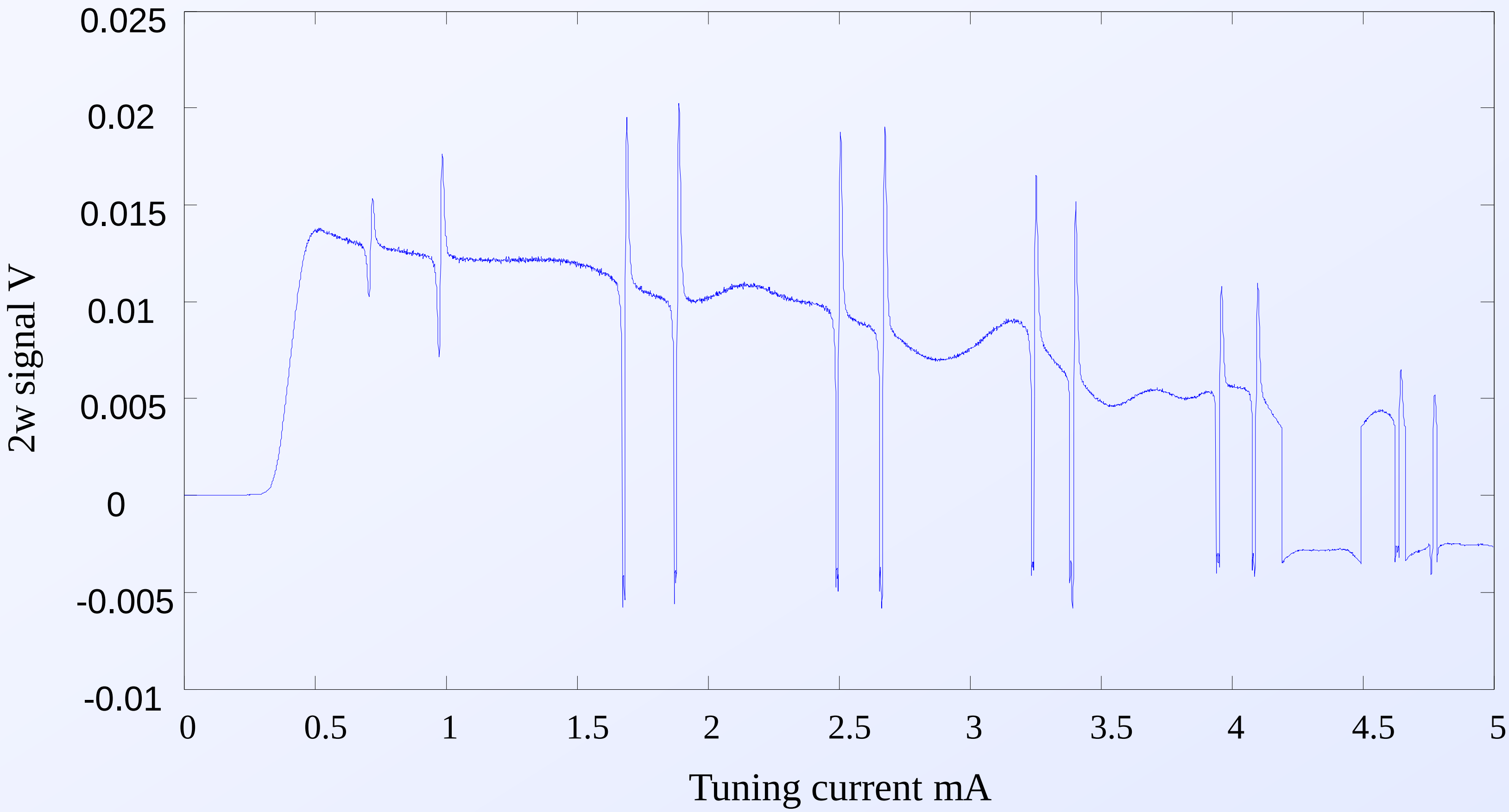
<u>Modulation parameters</u>

Amplitude: 15 uA

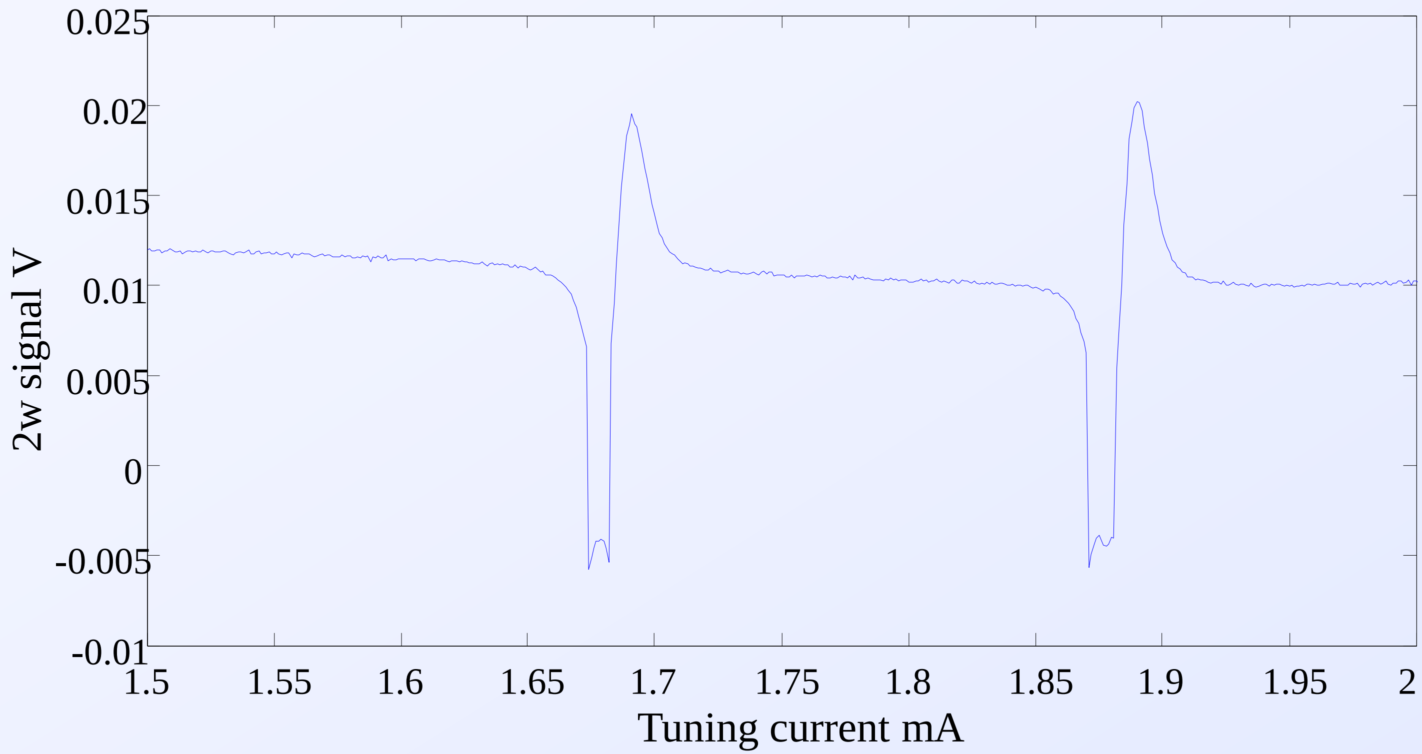
Frequency: 1kHz



Modulation parameters
Amplitude: 15 uA
Frequency: 1 kHz



<u>Modulation parameters</u>
Amplitude: 15 uA
Frequency: 70 kHz

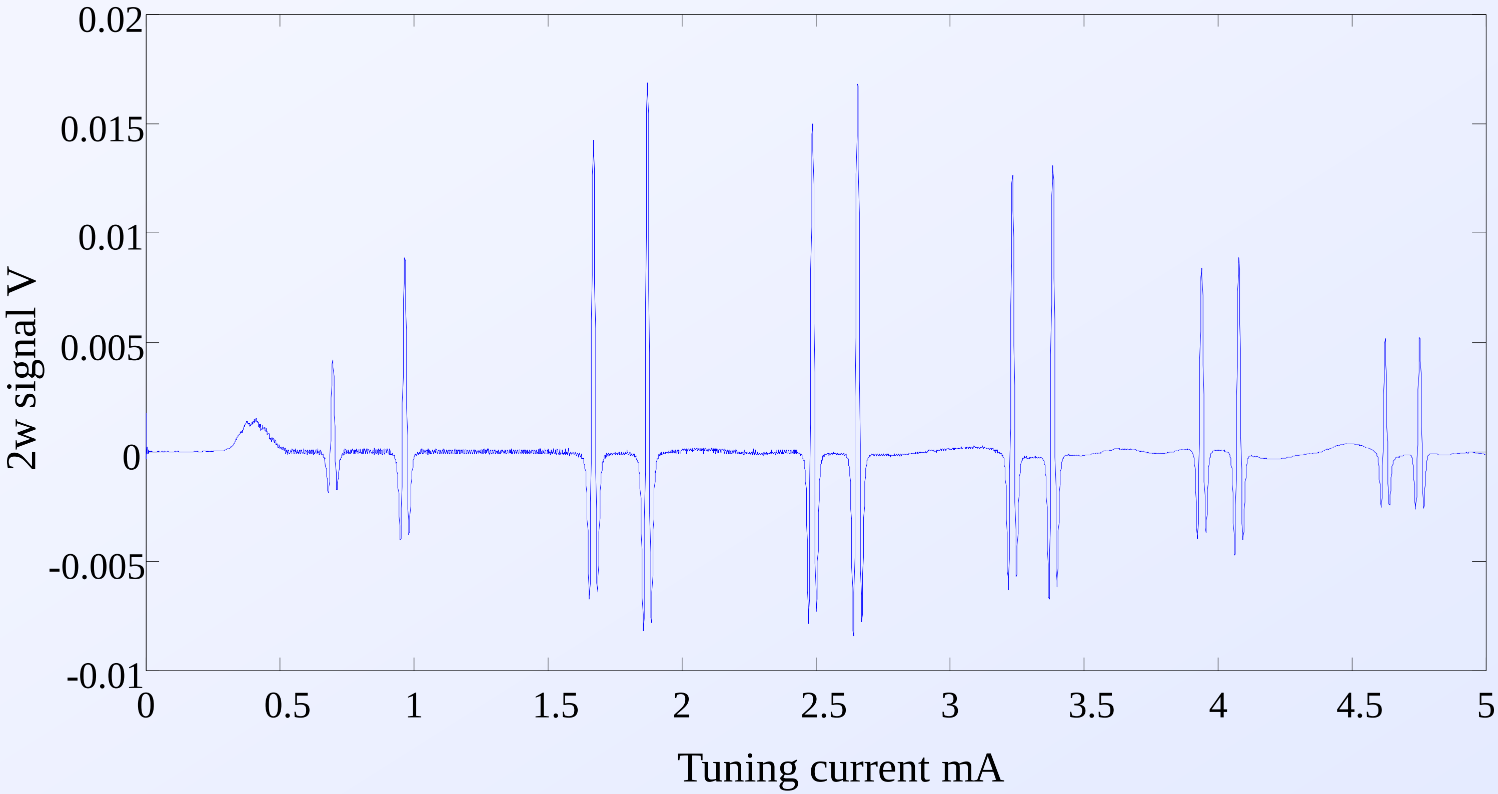


<u>Modulation parameters</u>

Amplitude: 15 uA

Frequency: 70 kHz

Oxygen amplitude scan line outs

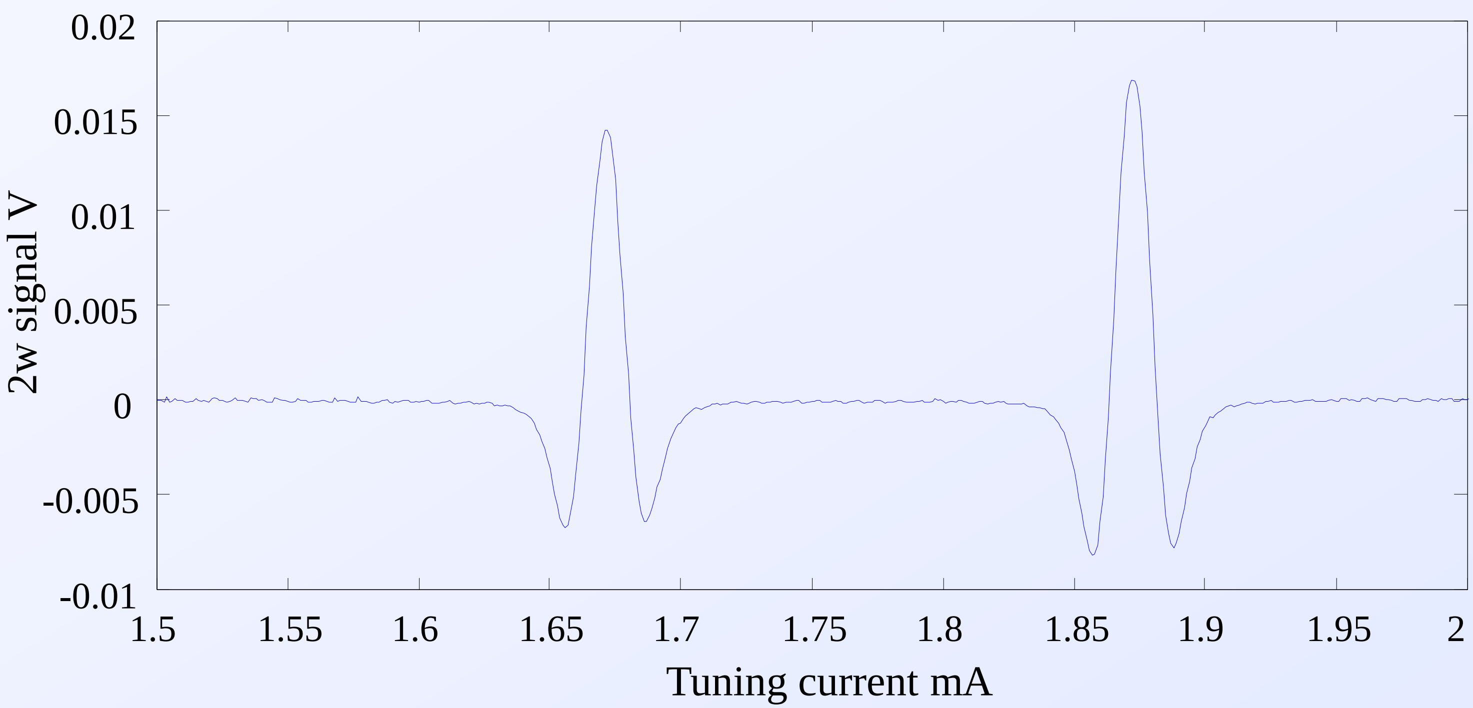


<u>Modulation parameters</u>

Amplitude: 15 uA

Frequency: 1 kHz

Oxygen amplitude scan line outs

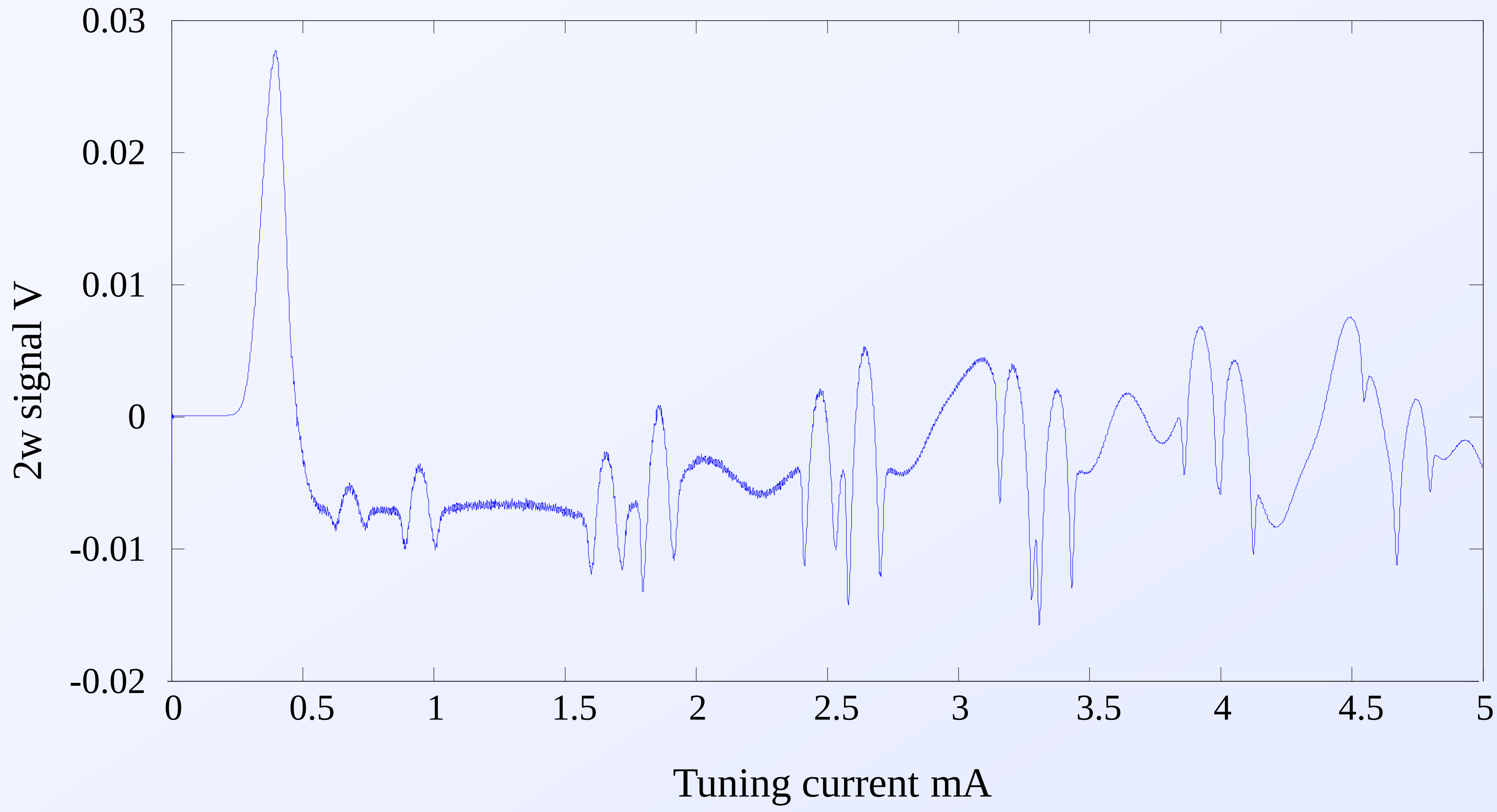


<u>Modulation parameters</u>

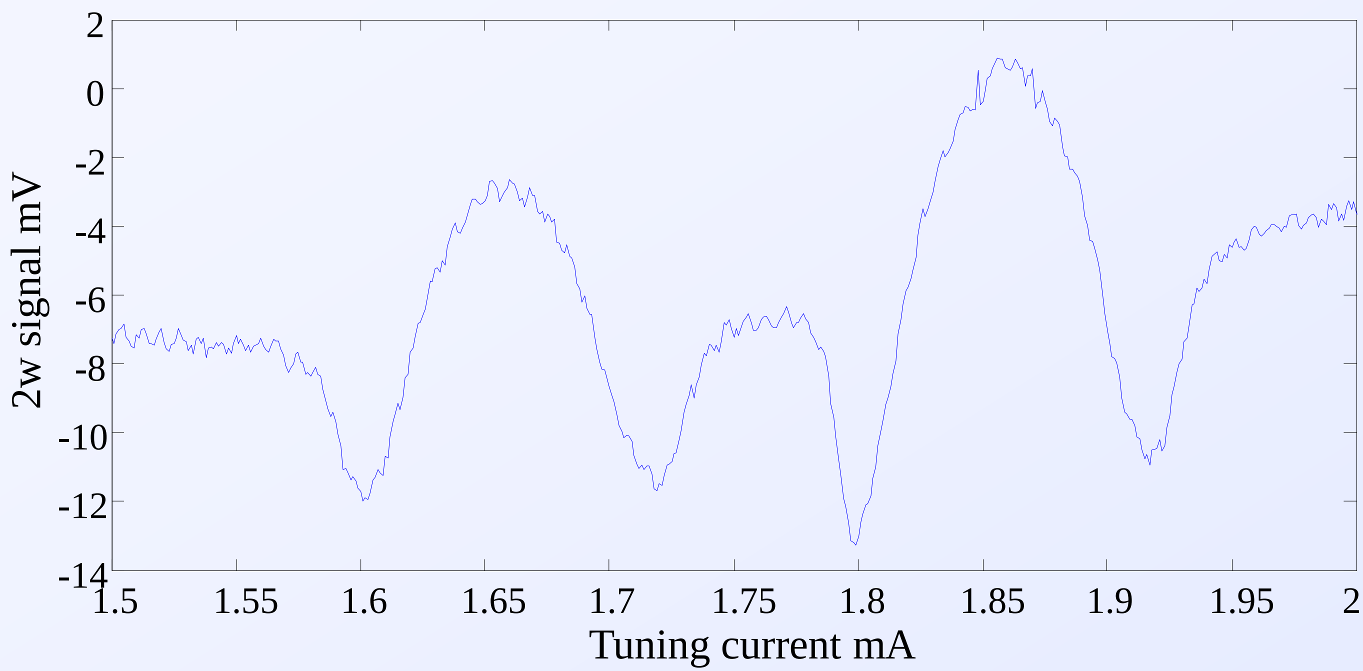
Amplitude: 15 uA

Frequency: 1 kHz

Oxygen amplitude scan line outs



<u>Modulation parameters</u>
Amplitude: 75 uA
Frequency: 1 kHz

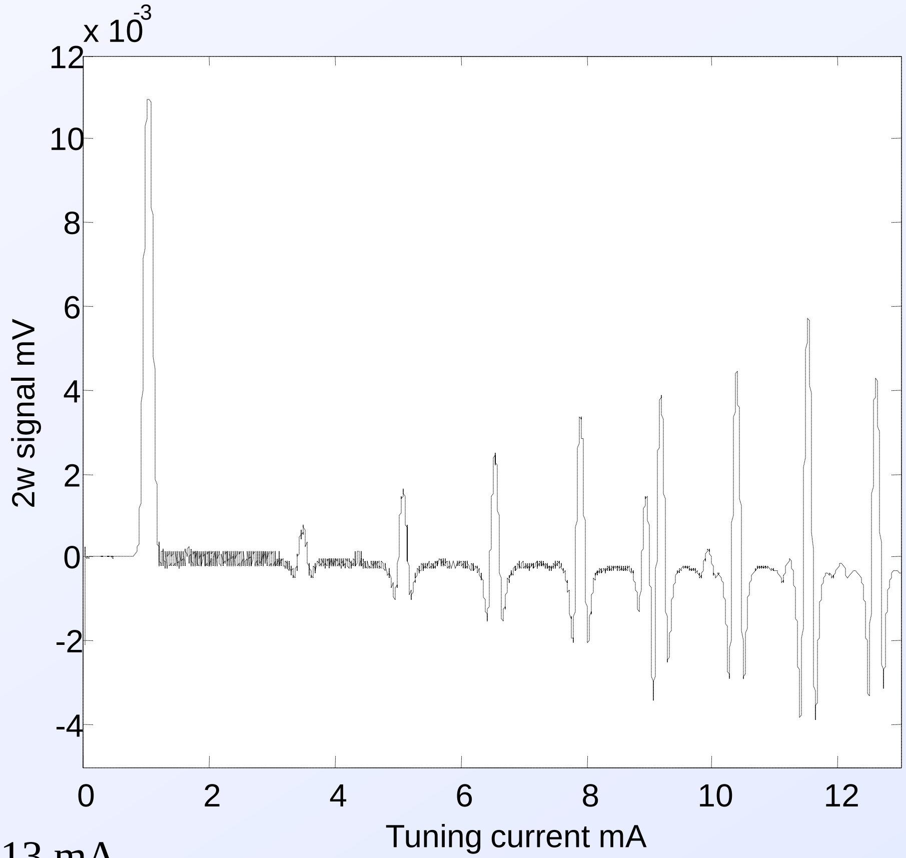


<u>Modulation parameters</u>

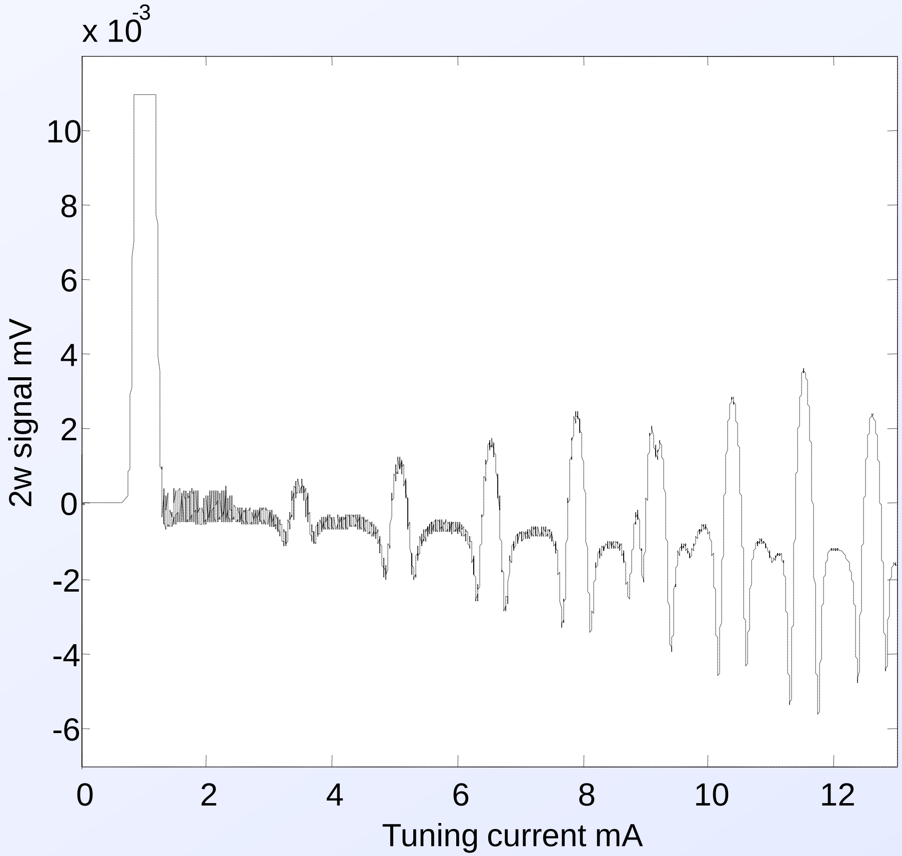
Amplitude: 75 uA

Frequency: 1 kHz

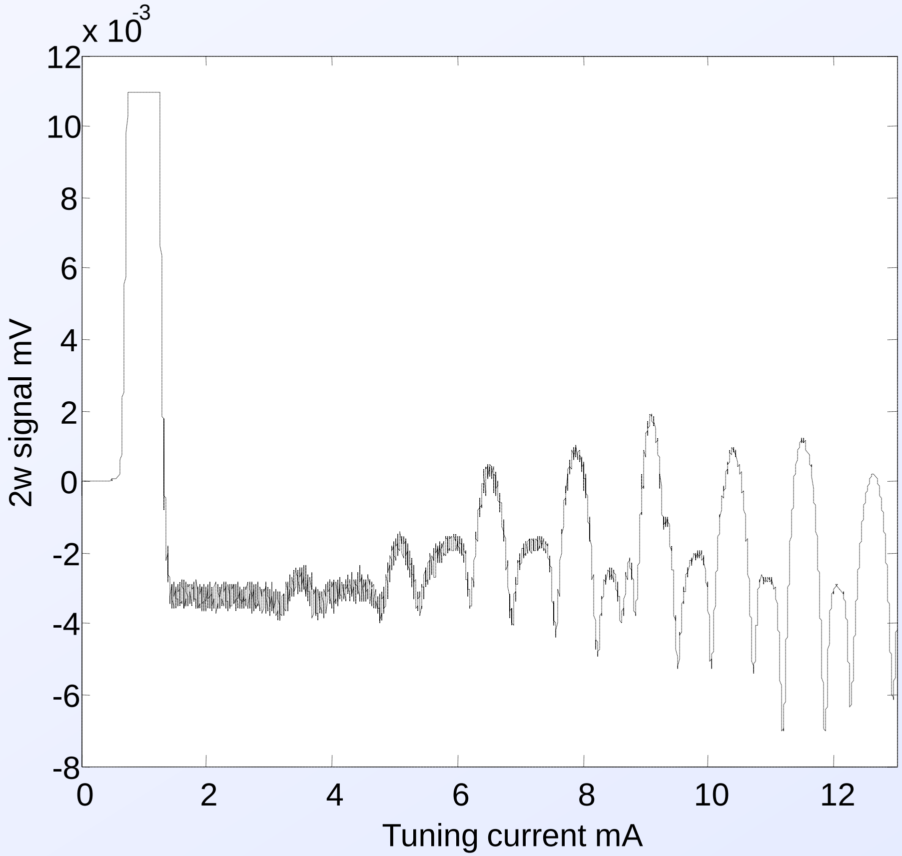
CO2 amplitude sweep



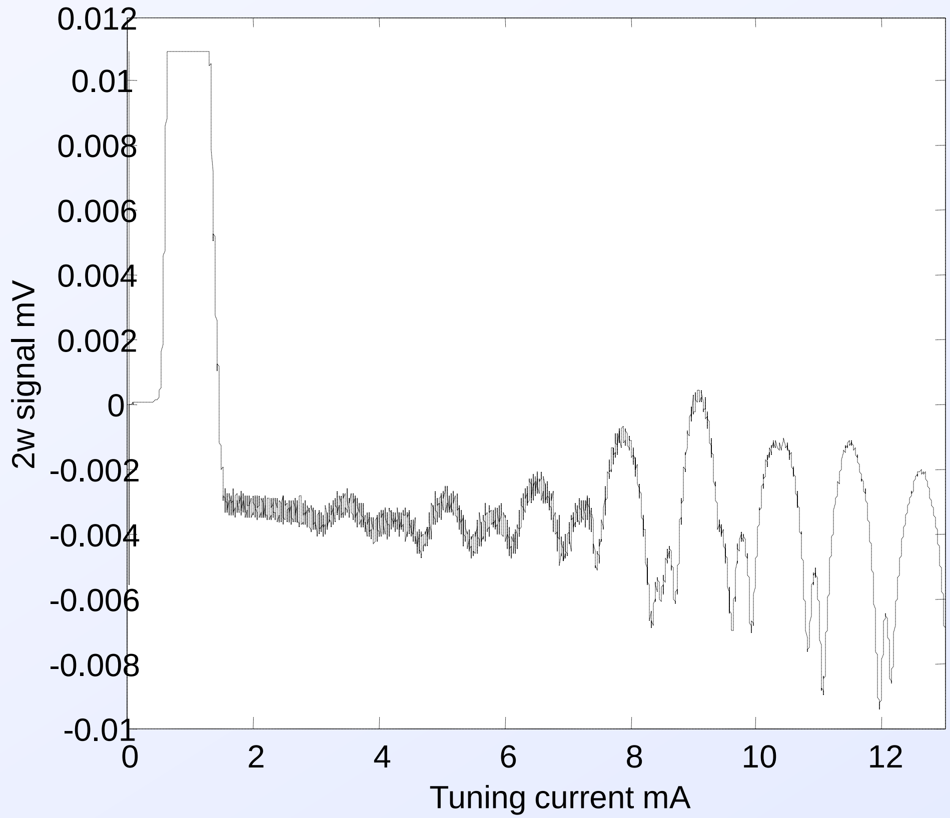
Tuning current: 0:0.002:13 mA
Amplitude: 125 uA
Frequency: 1 kHz



Tuning current: 0:0.002:13 mA
Amplitude: 250 uA
Frequency: 1 kHz



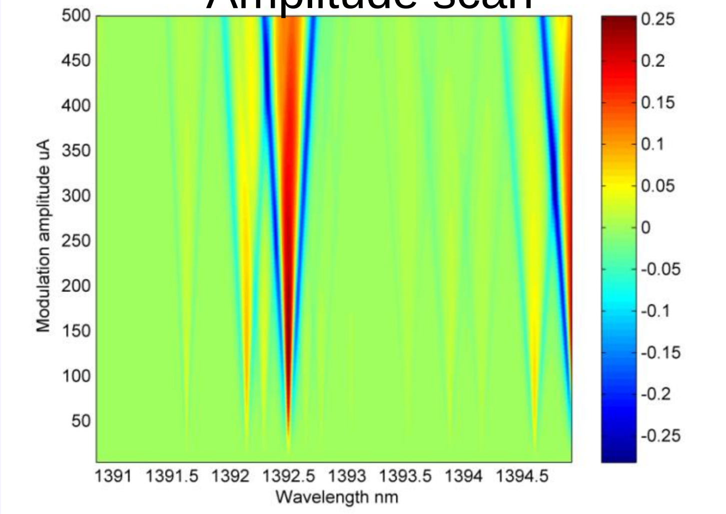
Tuning current: 0:0.002:13 mA
Amplitude: 375 uA
Frequency: 1 kHz

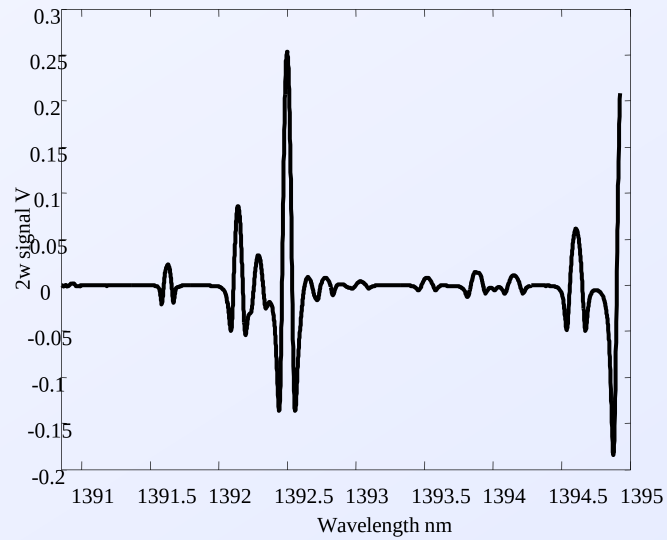


Tuning current: 0:0.002:13 mA
Amplitude: 500 uA
Frequency: 1 kHz

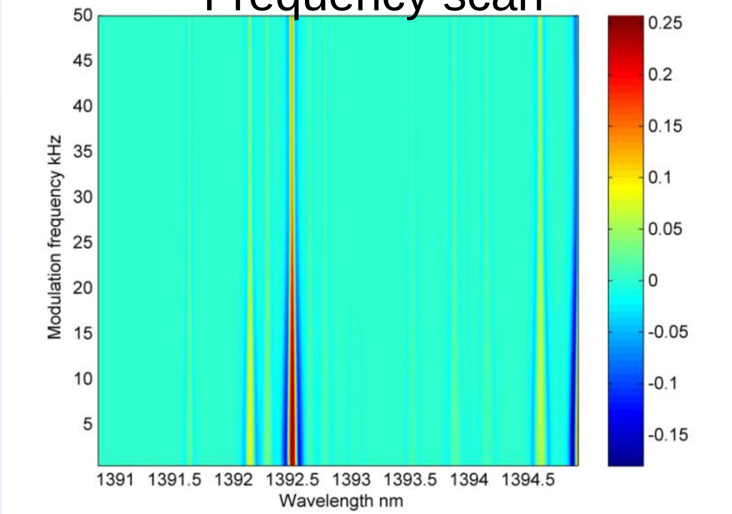
Water vapor (2-3%) in air

Amplitude scan

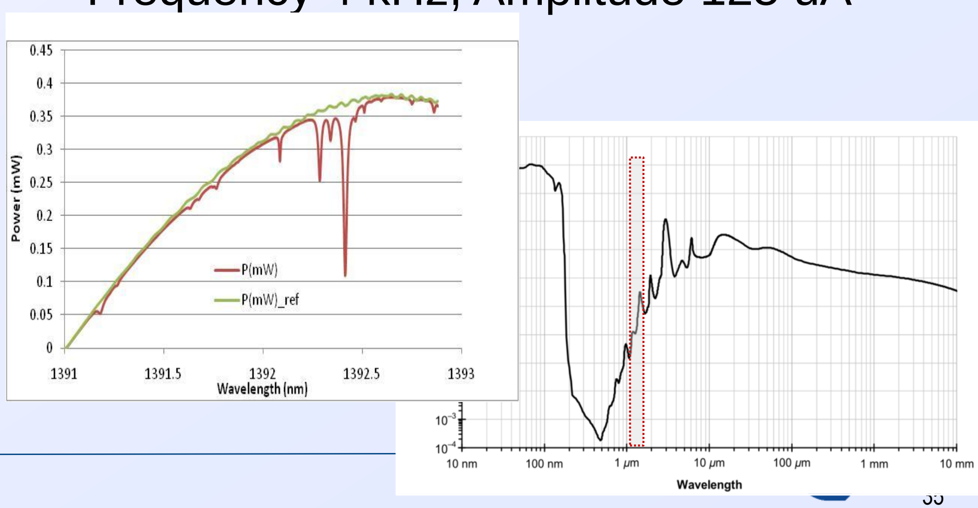




Frequency scan



Frequency 4 kHz, Amplitude 125 uA



Basic modeling assumptions

- Varying the current varies the total laser output power
- Varying the current also varies the laser temperature
- It is the varying temperature that drives the tuning of the laser center wavelength

Simple temperature model:

$$\frac{dT}{dt} = \frac{I^2 R}{M_{th}} - \frac{T - T_{back}}{\tau}$$ where $M_{th} \equiv Vol. \times \rho C_p$ and in steady-state $T_{ss} = T_{back} + \frac{\tau R}{M_{th}} I_{ss}^2$

Given $I(t) = I_0 + dI \sin \omega_o t$ then:

$$T(t) = T_{back} + \frac{\tau R}{M_{th}} I_{ss}^2 + \frac{2\tau R I_{ss} dI}{M_{th}(1 + \omega_o^2 \tau^2)} (\sin \omega_o t - \omega_o \tau \cos \omega_o t)$$

For the spectral power of the laser, assume output at a single temperature-dependent wavelength, with a current-dependent amplitude:

$$\frac{dP_{out}}{d\lambda} = (P_o + \frac{dP}{dI}(I - I_{ref}) + \frac{1}{2}\frac{d^2 P}{d\lambda^2}(I - I_{ref})^2)\delta(\lambda - \lambda_{cen})$$

$$\lambda_{cen}(T) = \lambda_{ref} + \frac{d\lambda}{dT}(T - T_{ref})$$

Basic modeling assumptions, continued

Gas Model: Assume an absorbing gas is present, with a single absorption line with a Lorentzian line shape; the spectral output is then modulated by a factor:

$$1 - \frac{\alpha}{1 + \frac{(\lambda - \lambda_g)^2}{\Delta\lambda_g{}^2}}$$

The detector integrates over wavelengths:

$$P_{detect} = \int \frac{dP}{d\lambda} d\lambda = (P_o + \frac{dP}{dI}(I - I_{ref}) + \frac{1}{2}\frac{d^2P}{dI^2}(I - I_{ref})^2)(1 - \frac{\alpha}{1 + \frac{(\lambda_{ref} - \lambda_g + \frac{d\lambda}{dT}(T - T_{ref}))^2}{\Delta\lambda_g{}^2}})$$

Normalize to P_o and choose I_{ref} such that $\lambda_{ref}=\lambda_g$ at $T=T_{ref}$:

$$\hat{I} \equiv (I - I_{ref})/I_{ref} \quad \hat{dI} \equiv dI/I_{ref} \quad s(t) = \sin\omega_o t \quad c(t) = \cos\omega_o t$$

P1 P2

$$\frac{P(t)}{P_o} = (1 + (\hat{I} + \hat{dI}s)(\frac{I_{ref}}{P_o}\frac{dP}{dI} + (\hat{I} + \hat{dI}s)\frac{I_{ref}^2}{2P_o}\frac{d^2P}{dI^2}))\times$$

$$(1 - \frac{\alpha}{1 + (\frac{T_{ref}}{\Delta\lambda_g}\frac{d\lambda}{dT}\frac{\tau R I_{ref}^2}{M_{th}T_{ref}})^2(\hat{I}^2 + 2\hat{I} + \frac{2(\hat{I}+1)\hat{dI}}{1+\omega_o^2\tau^2}(s - \omega_o\tau c))^2})$$

C

Note there are only 5 dimensionless model parameters, 4 of which can already be estimated from Mihai's existing data

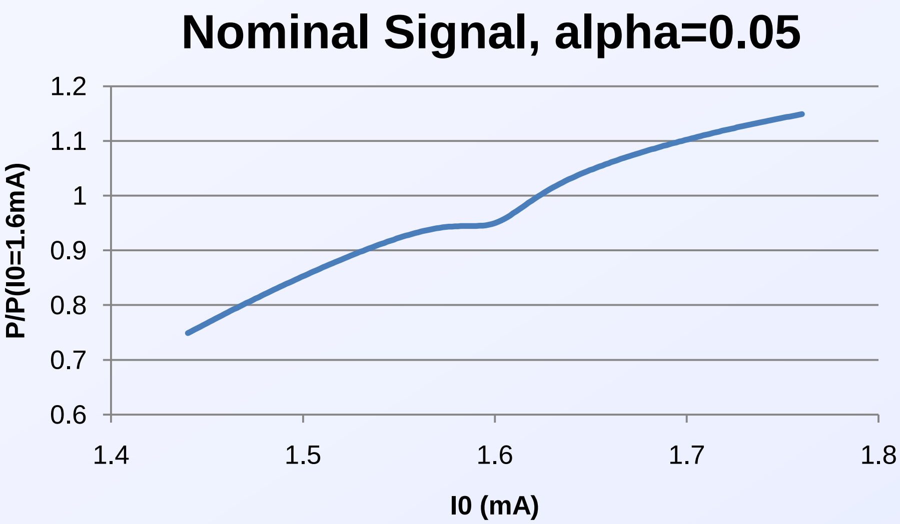
Assumed raw signal (normalized); alpha is a model parameter which scales the gas absorption

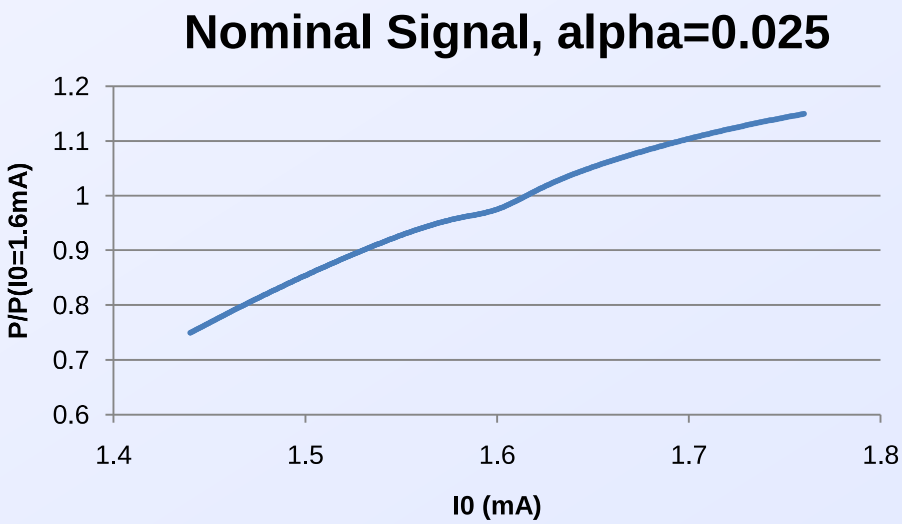
- Model params used in the following calcs:

P1 = 2

P2 = -5

C = 1000



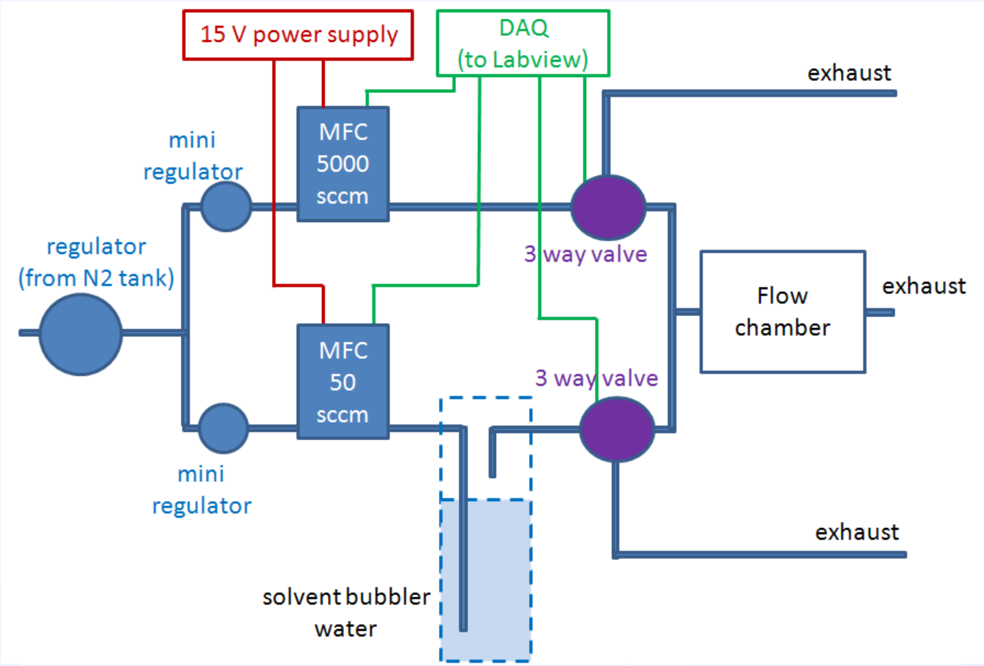


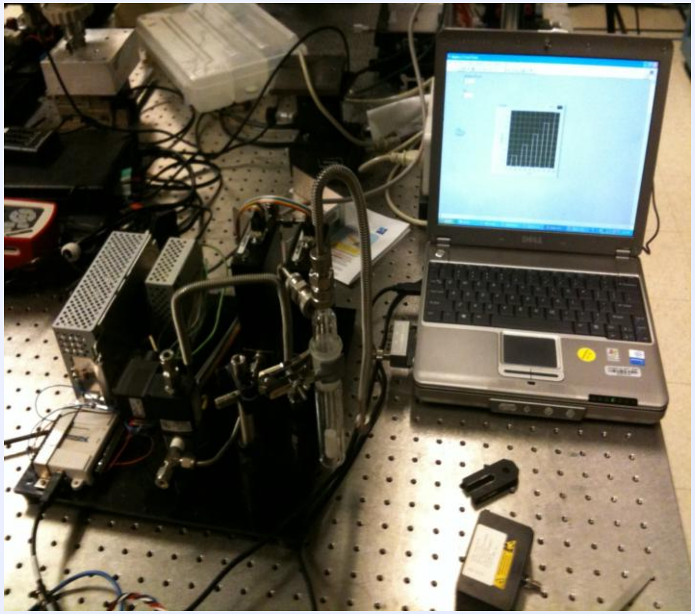
Couldn't finish the whole thing analytically, the following results are numerically calculated lock-in signals, i.e.:

$$\int \frac{P(t)}{P_o} \sin\left(n\omega_o + \phi\right) dt$$

Gas delivery systems for concetration studies

— Delivery system (completed)





- Gas Cell (in progress)